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Innovation for Maintenance Technology Improvements

MFPG

33rd Meeting

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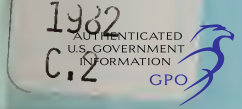

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MFPG
Innovation for Maintenance Technology Improvements

NBS special publication

Proceedings of the 33rd Meeting of the
Mechanical Failures Prevention Group,
held at the National Bureau of Standards,
Gaithersburg, MD, April 21-23, 1981

Edited by:

T. Robert Shives
William A. Willard

Center for Materials Science
National Measurement Laboratory
National Bureau of Standards
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FOREWORD

The 33rd meeting of the Mechanical Failures Prevention Group was held April 21-23, 1981, at the National Bureau of Standards in Gaithersburg, Maryland. The symposium was under the general coordination of the MFPG Technical Committee on Materials Durability Evaluation with A. W. Ruff of the National Bureau of Standards as Chairman. The program was organized under the chairmanship of A. J. Koury of the Naval Air Systems Command with technical support from M. J. Devine of General Technology, D. V. Minuti of the Naval Air Development Center, and M. B. Peterson of Wear Sciences, Inc. Publicity was handled by M. J. Devine. The organizers, the session chairmen, and especially the speakers, are to be commended for an excellent program.

Appreciation is expressed to William A. Willard, formerly of the National Bureau of Standards Fracture and Deformation Division and currently with the Naval Surface Weapons Center, for his assistance in editing, organizing and preparing these proceedings. Where possible, the papers in the proceedings are presented as submitted by the authors as camera ready copy. Some editorial changes and retyping were required.

Gratitude is expressed to Marian L. Slusser of the NBS Center for Materials Science for handling financial matters, to Annette Shives for typing, and to Jo Ann Lorden and Greta Pignone of the NBS Public Information Division for the meeting and hotel arrangements.

This proceedings is the first MFPG publication to go to press since NBS assumed the role as major MFPG sponsor in 1972 without the guidance of Harry C. Burnett. Mr. Burnett, former executive secretary and long time supporter of MFPG activities, died in September of 1981. He is missed by his many friends in MFPG and at NBS. His enthusiasm and genteel manner were an inspiration to all of us.

T. ROBERT SHIVES
Executive Secretary, MFPG

Center for Materials Science
National Bureau of Standards

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ABSTRACT

These proceedings consist of a group of 34 submitted entries (32 papers and 2 abstracts) from the 33rd meeting of the Mechanical Failures Prevention Group which was held at the National Bureau of Standards, Gaithersburg, Maryland, April 21-23, 1981. The subject of the symposium was maintenance technology improvement through innovation. Areas of special emphasis included maintenance concepts, maintenance analysis systems, improved maintenance processes, innovative maintenance diagnostics and maintenance indicators, and technology improvements for power plant applications.

Key words: fault detection/location system; lubrication; maintenance; maintenance management; maintenance technology; manpower utilization; reliability assessment.

UNITS AND SYMBOLS

Customary U. S. units and symbols appear in some of the papers in these proceedings. The participants in the 33rd meeting of the Mechanical Failures Prevention Group have used the established units and symbols commonly employed in their professional fields. However, as an aid to the reader in increasing familiarity with the usage of the metric system of units (SI), the following references are given:

NBS Special Publication, SP330, 1981 Edition, "The International System of Units."
ISO International Standard 1000 (1973 Edition), "SI Units and Recommendations for Use of Their Multiples."
IEEE Standard Metric Practice (Institute of Electrical and Electronics Engineers, Inc., Standard 268-1979).

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Certain trade names and company products are identified in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessaily the best available for the purpose. Views expressed by the various authors are their own and do not necessarily represent those of the National Bureau of Standards.

SESSION I

MAINTENANCE TECHNOLOGY AND MAINTENANCE CONCEPTS

CHAIRMAN: A. W. RUFF
NATIONAL BUREAU OF STANDARDS

MAINTENANCE TECHNOLOGY CONCEPT

A. J. Koury
Naval Air Systems Command
Washington, D. C. 20361

An examination of the scale of mechanical and structural failure can be readily estimated from the list of very recent equipment malfunctions receiving national attention shown on Figure 1. The first concerns a nuclear-power plant closed due to reactor and cooling system failure during October 1980. Not including equipment replacement cost, an expenditure of $800,000/day was incurred for a period exceeding ninety days! The second covers a major recall in automobile history due to the failure of two bolts --- over 6 million autos are involved! Consider several additional failures representing national concern (A) Flow control equipment identified as cause of failure at Three Mile Island Nuclear Power Plant -- estimated cost $1 billion (B) Improper valve component installation resulting in the total loss of a chemical processing plant in Newark, Delaware (C) Motor failure in a steel mill finishing plant -- in this instance a rapid repair costing $400,000 -- avoided a loss estimated at 30 million dollars. (D) Steel Reinforcing rods in concrete and bridge systems have been severely damaged from salt used to prevent highway icing, cost estimates for failures represents millions of dollars expended.

Every major industry, utility and government service involved with equipment operation has described failures of major cost and consequences. These failures also have a direct and significant impact on productivity.

Improvement in failure avoidance and problem solution is a mandatory national requirement. Innovative approaches based on technology clearly focused on safety, durability, reliability and operating economy, of a wide range of machinery and equipment can yield effective solutions.

Mechanical and structural failure prevention is critically dependent on a number of important disciplines listed in Figure 2. Requirements include 1) identification and assessment of the failure process, such processes include wear, corrosion, fatigue and fracture representing the more common modes, 2) the operational environment such as vibration, shock, humidity, temperature, salt, sand and contamination can accelerate severe damage, 3) materials and material processing including composition, heat treatment, surface coatings and surface finishing can be key determinants of service life, 4) assembly, transport and preservation involves training, manuals and publications, handling equipment, and protective materials required for effectiveness, 5) human performance covering knowledge, skill, experience and motivation

are vital elements.

Prior to describing the "Maintenance Technology Concept" and the factors involved with successfully linking research and development with failure prevention, a review of current programs for conducting equipment and plant maintenance will be reviewed.

PREVENTIVE MAINTENANCE

In the early days of industrial development and through much of its history, there has been primarily one approach to maintenance: Preventive Maintenance. There are still many adherents today with obvious justification. It only costs $4 to grease a bearing but $400 to replace it. While the bearing is being replaced several million dollars of production may be lost. In preventive maintenance those actions are taken which are necessary to forestall equipment deterioration. Where preventive maintenance is practiced, technology efforts have been mainly directed to improving two areas: management techniques and for improved tools and equipment which shorten the maintenance task times.

Maintenance management has gone from a random scheduling of tasks to a highly organized, minutely scheduled work system with accurate cost accounting and accountability. Computer systems analyse the work load and organize it efficently. CRT terminals have replaced maintenance manuals and provide rapid information acquisition. Some of the maintenance tasks taken over by computers are listed in Figure 3.

Another important development in preventive maintenance is simplified inspection and repair. "In situ" repairs are listed in Figure 4. These include leaks, under-water repair techniques, rebuilding of worn surfaces, repair of FOD damage to turbine blades, repair of composite structures, restoring surfaces which have been damaged by corrosion or erosion, crack repair, and machinery alignment. Analysis has shown that one of the most costly elements of the maintenance process is not the repair but the disassembly, removal and reassembly. Thus, the development of components such as bearings and seals which can be removed without extensive disassembly are particularly valuable.

The realization that many inspections are invalid and frequently unnecessary and often redundant, has led many organizations to abandon preventive maintenance as too costly. Secondly, it has been realized that maintenance actions often are the causes for systems to malfunction; that is, errors are committed during maintenance. Thus, other alternatives were investigated.

ON CONDITION MAINTENANCE

In "on condition" maintenance, actions are taken when inspections

or the operating characteristics of the equipment indicate that maintenance is required. Many of us use this approach to automobile maintenance. The literature reports successful use in a wide range of applications such as aircraft, appliances, and plant equipment.

Once success was achieved with certain applications, there was the natural inclination to expand the concept to other more critical ones. For critical applications it was necessary to get an early, positive indication of failure so that maintenance could be accomplished before failure actually occurred. This led to the concept of condition monitoring in which instruments and warning devices replaced the eyes and ears of maintenance and operating personnel. This more sophisticated approach to "on condition" maintenance is described in the following section.

CONDITION MONITORING

During the past 10 years a vast amount of work has been undertaken to develop and improve condition monitoring capabilities. The main thrust of the work has been to develop sensors and appropriate hardware to give some sort of a malfunction warning to the operator.

The concept of condition monitoring is not new. Temperature sensors, oil pressure indicators, fire lights, wear detectors, flow indicators, fluid level gages and power level sensors have always been used to give an indication of the condition of at least one component of a system. What was new was the idea that eventually all sensors would be connected to a single "black box" which would not only warn the operator of a problem but would tell him what was wrong and what to do about it.

The literature shows that condition mointoring has been applied to the types of machinery listed on Figure 5 with various degrees of success. This equipment includes gas turbine engines, diesel engines, turbomachinery, automobiles, trucks, tanks, buses, ships, transmissons, computers, construction machinery, space craft, nuclear power plants, and hydraulic systems. The major systems which have been used are listed on Figure 6. In the first approach critical sensors are specifically selected for each malfunction or component. This might be only a thermocouple or it would be a complete system. For example, the literature describes bearing monitors, structural fatigue monitors, corrosion detectors, wear indicators, misalignment, and a variety of other gages. The difficulty with the critical sensor approach is that in many systems a large number of sensors are required. Approaches were sought for a single technique which would detect a large number of different types of malfunctions. Another approach receiving the most attention has been vibration analysis. In this approach each malfunction produces a characteristic signal which can be recognized and interpreted by the analyser. Oil analysis measures the composition of wear particles in the oils to isolate facility components. Gas path

and exhaust analysis monitor the combustion process while IR analysis monitors "hot spots".

Although great strides are being made it is impossible to monitor everything. Monitoring has been most effective in systems of reduced complexity not requiring a multiplicity of sensors.

MODULARIZATION

Modularization is the design approach to maintenance. Essentially a machine is designed with easily replaceable modules. If service problems develop, the modules are interchangeable and replaced while the faulty module is repaired. Although this concept has been used successfully in consumer appliances and electronic equipment for many years, its use in complex machinery is just beginning. For example, a gas turbine engine is built in four modules viz. power turbine, hot section, cold section, and accessory section. The power turbine module consists of the turbine case, the turbine rotor assembly, the turbine drive shaft and the exhaust frame. The hot section includes the combustion liner, the turbine stator and rotor assemblies. The cold section has the output shaft, the front frame, the main frame, the compressor rotor and stator and the diffuser casing. The accessory section contains the various accessories. The main advantage is of course that the whole engine is not down while one part is being repaired. There are, however, disadvantages. The principal disadvantage is that maintenance personnel often take the path of least resistance and remove modules for trivial reasons. It is not uncommon to find a large increase in the "no defect" removals when this approach is used. What is needed is test equipment so that the need for module removement can be accurately determined. Performance records become of limited value since interchangeability can lead to loss of identity. However, the benefits gained in availability usually outweigh the disadvantages. This approach will probably find increased useage as demands for quick response maintainability increase.

RELIABILITY-CENTERED MAINTENANCE

Reliability-centered maintenance (RCM) is a technique for developing scheduled maintenance programs for aircraft, although the technique is equally applicable to other equipment. It was developed by United Airlines in 1965 and has since been adopted in principle by a large number of other airlines. The significant difference between this program and others is each maintenance task is directly related to component failure modes and their consequences. The process begins with the identification of all failure significant components. The functions of these components are then defined and possible failure modes are selected based upon component functions. Consequences of failure are identified as safety, availability, cost or failure producing. With this information, decision diagrams are then used to identify scheduled maintenance tasks. Four scheduled maintenance tasks

can be assigned:

On-condition inspection

Scheduled rework

Scheduled discard

Failure inspections

These tasks are then grouped into a specific maintenance program for a specific piece of equipment.

This approach basically selects from an all-encompassing preventive maintenance program (which inspects and repairs all components with equal vigor) those tasks which have a direct effect on maintenance objectives. Where RCM has been used maintenance costs have been reduced significantly. More extensive benefits of this program will be realized when the data base and information is expanded on service failure modes.

ANALYTICAL MAINTENANCE PROGRAMS

With preventive maintenance programs the main flow of work is from the manufacturer, through manuals, to maintenance personnel who effectively schedule and undertake the necessary tasks. With an analytical maintenance program there are strong inputs from maintenance as to what is done, when it is done, and how it is done. The basis for this program is a complete understanding of maintenance objectives and effective measurements of current maintenance operations. Such information is now available with computerized maintenance operations which make available records of all maintenance operations. The Navy 3M system is typical. All maintenance actions are recorded in a computer and can be recalled for review. This is illustrated in Figure 7 where the man hours associated with certain malfunctions are recorded. The malfunctions and the WUC's are pre-selected and the computer sums the maintenance man hours for each part and each malfunction. The value of such data is obvious. Components requiring excessive man hours can be investigated for specific details so that corrective measures can be taken in maintenance. For example, in Figure 8 leaking actuators are summarized. Failure analysis shows that the problem in all cases is actuator rod wear due to dirt trapped in the exclusion seal. A variety of maintenance approaches are available to reduce this sort of problem. These data identify component problem areas; however, additional data yields other kinds of information such as squadron differences, budget data, cost effectiveness, future design modifications, and research directions.

FAILURE CONTROL

With an effective analytical maintenance program equipment users are able to practice what might be called failure control, a positive approach to reducing maintenance costs. This can only be achieved by obtaining a complete understanding of service failures and then applying the appropriate technology to reduce these failures. There is extensive literature on the subject of component failures and ways that these failures can be avoided. This technology is often not considered in design because the designer is unaware of the potential of certain kinds of failure. Once these failures are observed in maintenance, appropriate changes can be instituted. Experience shows that most failures originate because of one of the conditions listed on Figure 9. Much more research is necessary to develop components more tolerable to these conditions and make failure control information available to designers and maintenance personnel so that an effective information linkage is established.

MAINTENANCE TECHNOLOGY CONCEPT

The Maintenance Technology Concept is a scientific approach to failure prevention and maintenance improvements. It stresses the continual application of demonstrated technology and recognizes a multi-disciplinary requirement shown on Figure 10 and involves structures, materials, tribology, corrosion, preservations, fracture mechanics, diagnostics, life predictions, repair processes, quality assurance and the life cycle phases of machinery. Failure prevention and effective maintenance based on this concept emphasizes:

- Research and development clearly focused on maintenance objectives.
- Performance information data base retrievable for design and management decisions.
- Implementation of new technology for performance upgrading and durability.
- In-situ structural monitoring.
- Non destructive inspections.
- Assessment of failure process - standardized classification and description.
- Assessment of repair process including repair verification.

The comprehensive plan for the Maintenance Technology Concept includes requirements for:

- Training
- Publications
- Personnel
- Engineering
- Support

A systems approach is inherent in this concept and an imaginative management linking technology advances with manufacturing, processing and maintenance operations as well as information data bases is needed on a sustained basis. The Maintenance Technology Concept involves the following three essential phases:

PHASE I - MAINTENANCE TECHNOLOGY INFORMATION BASE

(1) Review information/data from maintenance documents,

(2) On-site surveys for various levels of maintenance to inspect machinery, structure and equipment; discuss and examine maintenance procedures to determine current practice and techniques.

(3) Compilation and analysis comparing maintenance requirements and maintenance capabilities.

(4) Determine condition of machinery/equipment/structure and causes of degradation.

(5) Assessment covering optimum materials, processes, treatment, repair and inspection procedures.

PHASE II - MATERIAL/PROCESSES FOR EFFECTIVE MAINTENANCE

(1) Define optimum procedures for detection and interpretation of the degree of material degradation.

(2) Determine from data generated under Phase I latest applicable technology for increasing equipment performance and service life.

(3) Define optimum materials and processes for treatment and repair for application at the various levels of maintenance.

(4) Initiate verification procedures.

(5) Conduct on-site demonstrations of improved procedures.

PHASE III - TECHNICAL REQUIREMENTS FOR MAINTENANCE IMPROVEMENTS

(1) Revise maintenance publications, e.g., manuals and rework specifications.

(2) Define or recommend design/material changes where required.

(3) Recommend R&D starts covering technology voids.

In this approach, the earliest exploitation of new technology will be emphasized, viz:

(a) Identification of improved materials and processes for various levels of maintenance.

(b) Implement/accelerate use of the improved technology in new production and manufacturing processes.

(c) Utilization of innovations in technology on a continual basis for maintenance improvements.

SUMMARY

Significant technical advances are the critical elements of this new approach to maintenance. Technology can be the vital element of the maintenance plan resulting from a policy emphasizing increased durability and equipment availability with effective cost control. Examples of maintenance technology available to support this policy are:

1. Use of computer systems to optimize data storage, retrieval, dissemination as well as maintenance scheduling, record and analyse service problems, and control inventories.

2. Application of maintenance models to weigh complex alternatives.

3. Apply condition monitoring instrumentation for early warning of impending failures or malfunctions.

4. Introduce rapid inspection and repair techniques.

5. Require failure resistant designs.

6. Use improved maintenance materials and processes.

The ultimate goal of maintenance technology is to achieve a specified period of trouble-free operation followed by an all-inclusive maintenance period. With the new and emerging technology we are now

approaching that goal. The major conclusion is that the widest possible benefit to industry and government can be achieved from a national program exploiting the maintenance technology concept.

MECHANICAL/STRUCTURAL FAILURE
RECENT EXAMPLES

- NUCLEAR-POWER PLANT MALFUNCTION
  EXPENDITURE: $800,000/day
- AUTOMOBILE BOLT FAILURES
  RECALL: 6 MILLION PLUS AUTOS
- TMI - FLOW CONTROL FAILURE
  LOSS: 1 BILLION PLUS DOLLARS
- CHEMICAL PROCESS VALVE FAILURE
  RESULT: LOSS OF CHEMICAL PLANT
- STEEL MILL FINISHING PLANT - MOTOR FAILURE
  EXPENDITURE: $400,000 RAPID REPAIR TO
  AVOID A $30 MILLION LOSS
- HIGHWAY/BRIDGE SYSTEM REINFORCEMENT FAILURE
  COST: MULTI-MILLION DOLLARS

Figure 1

MAINTENANCE TECHNOLOGY DISCIPLINES

- STRUCTURES
- MATERIALS
- TRIBOLOGY
- CORROSION
- PRESERVATION
- FRACTURE MECHANICS
- DIAGNOSTICS
- NONDESTRUCTIVE INSPECTION
- REPAIR PROCESS
- LIFE PREDICTION
- QUALITY ASSURANCE

Figure 2

COMPUTER USES IN MAINTENANCE

- MATERIALS INVENTORY AND ORDERING
- SCHEDULING MAINTENANCE AND INSPECTIONS
- REPORTING MAINTENANCE HISTORY
- COST ANALYSIS AND CONTROL
- ISSUING WORK ORDERS
- CRITICAL PATH NETWORK ANALYSIS

Figure 3

"INSITU REPAIRS"

- LEAKS
- UNDERWATER REPAIR TECHNIQUES
- WEAR
- TURBINE BLADES
- COMPOSITE STRUCTURES
- CORROSION AND EROSION DAMAGE
- CRACK REPAIR
- ALIGNMENT
- COMPONENT REPLACEMENT

Figure 4

CONDITION MONITORED EQUIPMENT

- GAS TURBINE ENGINE
- DIESEL ENGINES
- TURBOMACHINERY
- AUTOMOBILES
- TRUCKS
- TANKS
- BUSES
- SHIPS
- TRANSMISSIONS
- COMPUTERS
- CONSTRUCTION MACHINERY
- SPACE CRAFT
- NUCLEAR POWER PLANTS
- HYDRAULIC SYSTEMS

Figure 5

CONDITION MONITORING APPROACHES

- CRITICAL SENSORS
- VIBRATION
- OIL ANALYSIS
- GAS PATH ANALYSIS
- EXHAUST ANALYSIS
- IR ANALYSIS

Figure 6

A6 AIRCRAFT STRUCTURE
330 /A/C 1 YEAR OPERATION

				MALFUNCTIONS (Manhours)							
Work Unit Code	Identification	Total Hours	Total Incidences	Corroded	Broken	Cracked	Leaking	Stuck	Worn	Loose	Improper Lubrication
1121500	**Wing Skin**	12,778	1752	**11,429**	331	170	534	0	127	8	0
1113000	Misc Access Doors/Panels	11,122	2295	5,723	3,206	1,057	143	41	299	316	10
1113100	Forward Engine Access Door	9,491	1659	4,846	3,505	533	8	237	147	91	10
1113800	Access Panel	7,775	1646	4,080	2,071	762	72	6	290	162	18
1432100	**Flaperon Actuator**	5,724	139	2	19	2	**5,622**	60	10	7	4
1481400	Slat Assembly	4,895	533	3,559	595	346	7	54	183	4	3
1121200	Wing Outer Panel	4,591	296	2,880	159	783	591	0	103	1	0
1121100	Wing Inner Panel	4,558	378	3,991	27	87	434	2	0	0	3
1411200	Flaperon Skin	4,124	442	3,170	45	37	0	40	3	0	0
1118300	Boarding Ladder Assembly	3,972	879	2,331	774	501	6	27	283	19	6
1442100	Rudder Actuator	3,919	99	9	92	0	2,289	42	79	23	0
1452100	Stabilizer Actuator	3,496	83	16	62	0	2,272	1	20	0	0
1131200	Vert Stabilizer Skin	3,275	495	3,024	110	55	0	0	12	14	0
1116100	Ext Equipment Platform	2,494	538	1,127	872	180	15	43	123	79	4
1121400	Wing Leading Edge	2,578	407	1,778	79	60	70	2	244	21	0
1113500	Aft Engine Access Door	2,457	420	1,975	317	74	0	18	35	22	1
1113600	Tail Pipe Access Door	2,383	369	1,819	368	60	12	0	106	7	0
1311100	MLG Shock Strut	2,385	313	1,114	36	465	492	122	10	2	116
1311000	MLG Mechanical Components	2,365	291	1,144	217	77	47	162	99	12	578
1321100	NLG Shock Strut	2,559	167	1,464	9	3	897	4	16	4	147
1451100	Hor Stabilizer Cable	2,453	46	4	1,979	0	120	0	349	6	0

Figure 7

A6 ATTACK AIRCRAFT
LEAKING MALFUNCTIONS
330 AIRCRAFT 1 year operation

Component	Incidents	O & I Manhours
Flaperon actuator	138	5622
Rudder actuator	79	2289
Stabilizer actuator	71	2272
MLG sequence valve	82	1321
MLG hydraulic lines	104	1215
NLG shock strut	52	897
NLG Retract cylinder	34	753
Wing structure	55	711
Wing outer panel	63	591
Wing skin	39	534
MLG retract actuator	64	500
MLG shock strut	26	492
TOTAL	807	17,197

Figure 8

CONDITIONS RESPONSIBLE FOR FAILURES

- ENVIRONMENT
- CONTAMINATION
- MISALIGNMENT AND POSITIONING
- EXCESSIVE LOADS OR TEMPERATURES
- VIBRATION
- MATERIAL DEGRADATION
- INADEQUATE LUBRICATION
- SHOCK LOADS
- DAMAGE

Figure 9

FOCUS
MAINTENANCE TECHNOLOGY CONCEPT

SCIENTIFIC APPROACH STRESSING TECHNOLOGY INNOVATION FOCUSED ON IMPROVEMENTS FOR SAFETY, RELIABILITY, DURABILITY & OPERATING ECONOMY.

MANAGEMENT INITIATIVES LINKING TECHNOLOGY ADVANCES WITH MANUFACTURING, PROCESSING, AND MAINTENANCE AS WELL AS INFORMATION SYSTEMS ON A SUSTAINED BASIS.

Figure 10

INNOVATION FOR MAINTENANCE TECHNOLOGY IMPROVEMENTS

Harry Rolka
Dow Corning Corporation
Midland, Michigan 48640

Abstract: The high cost and complexity of today's industrial operation makes it imperative that maintenance technology be put to work. In 1980 American industry spent in the range of 246 billion dollars in maintenance costs for plant facilities and equipment. These estimates do not take into consideration the cost of lost sales caused by production downtime and poor product quality. The need and opportunity for skilled, results oriented maintenance administrators has never been better nor more important. The address will focus on the more critical maintenance problems facing industry; their impact and some innovative productivity practices and concepts that hold great promise for the future.

Key words: Maintenance; maintenance costs; maintenance technology; technology centers; technology innovation.

It is essential, I believe, that we occasionally step back from our daily job activities and take stock. We should reassess our goals, priorities, and performance, in light of present and future needs. When we do, these needs become better defined, and meeting them means "taking on a challenge" rather than simply "dealing with a problem."

We have an opportunity during these next three days to engage in this kind of reassessment, thanks to this joint Symposium sponsored by the Mechanical Failures Prevention Group of the National Bureau of Standards, and the Naval Air Systems Command. Although my background is primarily with chemical processing, associates from other fields assure me that our maintenance operations are far more similar than dissimilar. So with this in mind, I'm pleased to be here to share with you my experiences and ideas for meeting some of industry's more critical maintenance challenges.

First, an understanding of what is meant by "maintenance technology" -- and its economic significance -- is in order. This will provide the basis from which to discuss innovative productivity practices and concepts that hold great promise for the future.

Broadly speaking, Webster defines "technology" as "the systematic treatment of an art; an applied science or a technical method of achieving a practical purpose." A good example is Thomas Edison's development of the electric light bulb after 50,000 experiments.

I will define "maintenance technology" as "the systematic and scientific approach to preserving a plant's physical facilities and equipment in optimum working order." And, to do this often requires the dogged persistence of Edison - who remarked to his flustered colleagues, "Well, at least we now know of 50,000 things that will not work." Faced with today's complex and costly industrial operations, maintenance technology must be vigorously developed and applied. U.S. companies spent approximately 246 billion dollars in 1980 to maintain plant facilities and equipment. (This does not include the cost of lost sales resulting from production downtime and poor product quality.) The statistical comparisons shown in figure 1 illustrate the economic impact of maintenance costs.

After looking at this, you might say, "Great, maintenance operations is big business, but it's still not getting all the funds it needs That's probably true. But, we could make that money go a lot farther. Industrial consultants tell us that 30% -- about 75 billion dollars -- is wasted through poor management. A list of the causes of this waste are shown in figure 2.

It's important to note, that these same experts put the blame for this situation squarely on top management. This is because top management does not understand maintenance operations. For this reason I propose to you that the greatest single challenge facing maintenance managers today is closing the credibility gap between themselves and corporate executives. Effective maintenance managers will leave the tenuous safety of their "trenches and pillboxes" and take on all competitors vying for executive management support and limited cash resources. These battles will be won by using the same weapon the competitors use: knowing and selling the "bottom line" financial advantages, payback, and productivity improvements of your proposals. Maintenance administrators must speak in the financial terms executives understand -- cost analysis, economic evaluation, and cost/benefit comparisons. The successful manager needs to have a "fighter pilot mentality" of knowing the mission, the competition, and tenaciously pursuing the objective. We should keep in mind that the requirements for a good maintenance operation are the same as for any other business operation. A brief list of important maintenance requirements is shown in figure 3.

The maintenance picture is changing as more companies come to the realization that maintenance is the single largest controllable cost in the plant. In these companies effective maintenance administrators are finding top management support. New and innovative productivity practices and concepts are being implemented. Some of these improvements are worth mentioning.

I Maintenance Technology Centers (figure 4)

- Typical Charter
- Broad Representation
- Annual Reviews with Executive Management

II Capitalization Improvement

- Buying Current Technology
- Increasing Utilization of Industrial Robots
- Computerization of Operations

III Latest Instrumentation Training and Manpower Trends

- Traditional Instrumentation is Changing
- Technical Specialists for:
  - Process Computers
  - On-Stream-Analyzers
  - Electronic Controls

IV Fifth and Sixth Shift Operations

- Humanization of the Shift Worker (figures 5, 6)

V Team Action Circles (Quality Circles)

VI Exotic Materials of Construction

VII Non-Destructive Testing

- Vibration Analysis
- Ultrasonic Testing
- Fiber Optic Inspection Equipment
- Thermovision Equipment

VIII Multi-skill Craftsmen

- Electrical/Instrument Combinations
- Mechanical Craftsmen

Recent studies by the Brookings Institute on labor productivity estimates that implementation of technological innovation provides 44% of this nation's productivity improvement. So I will close with the same statement I started with -- the high cost and complexity of today's industrial operations makes it imperative that we put maintenance technology to work. Let's renew our commitment as maintenance professionals to assure this happens.

1980 COST COMPARISONS

* INDUSTRIES' MAINTENANCE COSTS ----- 246 BILLION DOLLARS

* AMERICAN'S TOTAL TAX BILL --------- 750 BILLION DOLLARS

  FEDERAL - 520 BILL. DOLLARS
  LOCAL & STATE - 230 BILL. DOLLARS

* INDUSTRIES' THEFT LOSSES ---------- 40 BILLION DOLLARS

* INDUSTRIES' ABSENTEEISM COSTS ----- 20 BILLION DOLLARS

  10 BILLION DOLLARS ATTRIBUTED TO
  POOR ATTITUDE AND LACK OF
  JOB COMMITMENT
  GM'S ANNUAL ABSENTEEISM COST IS
  1 BILL. DOLLARS

* RAILROAD MAINTENANCE COST --------- 11.3 BILLION DOLLARS

* THREE MILE ISLAND ESTIMATED REPAIR AND
  REFURBISHING BILL ------------ 1 BILLION DOLLARS
  (PLUS EIGHT YEARS)

Figure 1

CAUSES OF MAINTENANCE WASTES

* LACK OF MANAGEMENT COST CONTROL.

* LACK OF GOOD EQUIPMENT REPAIR RECORDS AND LITTLE ENGINEERING ANALYSIS OF EQUIPMENT FAILURES.

* POOR OPERATOR TRAINING RESULTING IN IMPROPER EQUIPMENT OPERATION.

* MISMANAGEMENT OF SPARE PARTS INVENTORIES AND MAINTENANCE SUPPLIES.

* INEFFICIENT PLANNING AND SCHEDULING.

* LACK OF PREVENTIVE MAINTENANCE PROGRAMS.

* LACK OF EFFECTIVE USE OF NON-DESTRUCTIVE TESTING AND DIAGNOSTIC EQUIPMENT.

* NO INCENTIVES TO ENCOURAGE BRIGHT SUPERVISORS AND ENGINEERS TO GET INTO MAINTENANCE.

* LACK OF COORDINATION BETWEEN PRODUCTION AND MAINTENANCE.

Figure 2

IMPORTANT MAINTENANCE REQUIREMENTS

I DEVELOP A GOOD ORGANIZATION AND INSTALL THE MOST EFFECTIVE MANAGERS AND SUPERVISORS YOU CAN FIND.

- CENTRALIZED, DECENTRALIZED AND MATRIX ORGANIZATIONS ALL WORK IF MANAGED PROPERLY.

II DEVELOP SEVERAL HISTORIC MAINTENANCE INDICES THAT MEASURE YOUR TEAM'S PERFORMANCE. TYPICAL INDICES

- MAINTENANCE COST PER UNIT OF OUTPUT
- EQUIVALENT MANPOWER PER UNIT OF OUTPUT
- EQUIPMENT DOWNTIME OR UTILIZATION MEASUREMENTS
- OVERTIME RECORDS
- ABSENTEEISM RECORDS
- CAPITALIZATION OF EXPENSE WORKERS
- WORK SAMPLING

III IMPLEMENT AN EFFECTIVE MANAGEMENT BY OBJECTIVES PROGRAM (MBO) WITH QUARTERLY REVIEWS. GAIN COMMITMENT. ASSIGN ACCOUNTABILITY.

IV CONTROL COSTS AND PEOPLE RESOURCES

V REWARD GOOD PERFORMERS

VI RETRAIN POOR PERFORMERS

Figure 3

C H A R T E R

MAINTENANCE TECHNOLOGY CENTER

PRIORITY I — DEVELOP MAINTENANCE TECHNOLOGY, PRIORITIZE AND ASSIGN MULTI PLANT OR CRITICAL MAINTENANCE PROBLEMS TO SKILL SPECIALISTS OR THE SKILL CENTER TASK FORCE FOR SOLUTION. COORDINATE IMPLEMENTATION OF CORRECTIONS WITH APPROPRIATE CONSIDERATION FOR SAFETY AND COSTS. ELIMINATE DUPLICATION OF EFFORT.

PRIORITY II — OPERATE AS A CLEARING HOUSE FOR MAINTENANCE TECHNOLOGY AND INFORMATION.

A. MAINTAIN TECHNICAL LIBRARY OF RECORDS AND REPORTS.
B. MAINTAIN AND DISTRIBUTE UPDATED LIST OF TECHNOLOGY BOARD MEMBERSHIP AND SKILL SPECIALISTS.
C. COMMUNICATE MAINTENANCE TECHNOLOGY.

PRIORITY III — ASSIST PLANTS IN IMPROVING MAINTENANCE PROGRAMS.

PRIORITY IV — DEVELOP INDICES TO MEASURE PLANT AND CORPORATE MAINTENANCE COST EFFECTIVENESS, PRODUCTIVITY AND EQUIPMENT ON LINE TIME.

PRIORITY V — IMPROVE CAPITAL UTILIZATION AND PRODUCTIVITY BY MAXIMIZING ON-LINE-TIME WHILE OPTIMIZING BOTH MAINTENANCE COST AND INITIAL CAPITAL.

Figure 4

5 SHIFT SYSTEM
40 HRS/WEEK

	M	T	W	T	F	S	S	TOTAL HOURS
1	-	N	N	N	N	N	N	48
2	N	-	L	L	L	L	L	48
3	L	L	-	-	M	M	M	40
4	M	M	M	M	-	-	-	32
5	D	D	D	D	D	-	-	40
								208

N = NIGHTSHIFT
L = LATE SHIFT
M = MORNINGSHIFT
D = DAYSHIFT

= 41.6 HRS/WEEK

	OFF-HOURS DURING WEEK	OFF-HOURS WEEKEND
SHIFT 1	24	—
SHIFT 2	56	—
SHIFT 3	56	—
SHIFT 4	—	89
SHIFT 5	—	54.5

+ 10.5 EXTRA FREE DAYS/YEAR

Figure 5

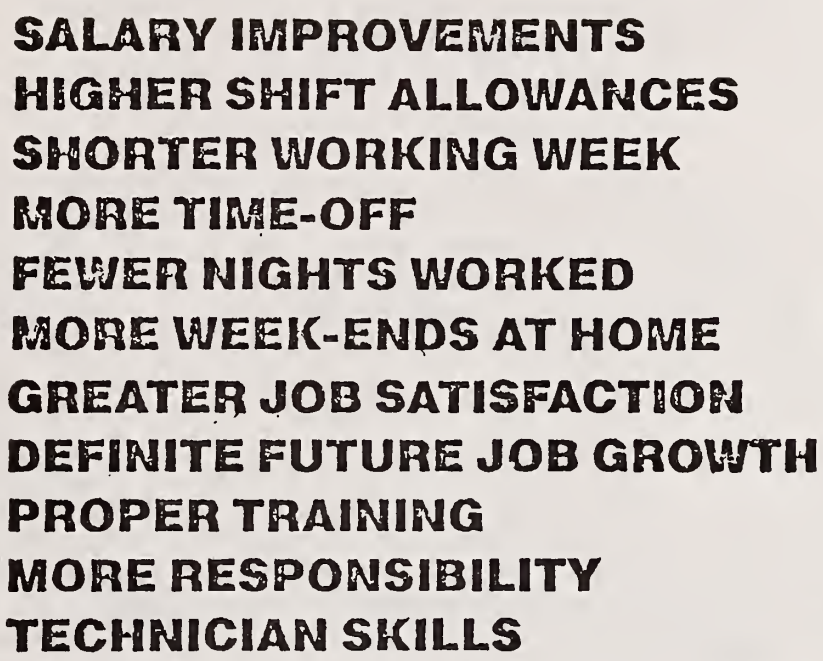
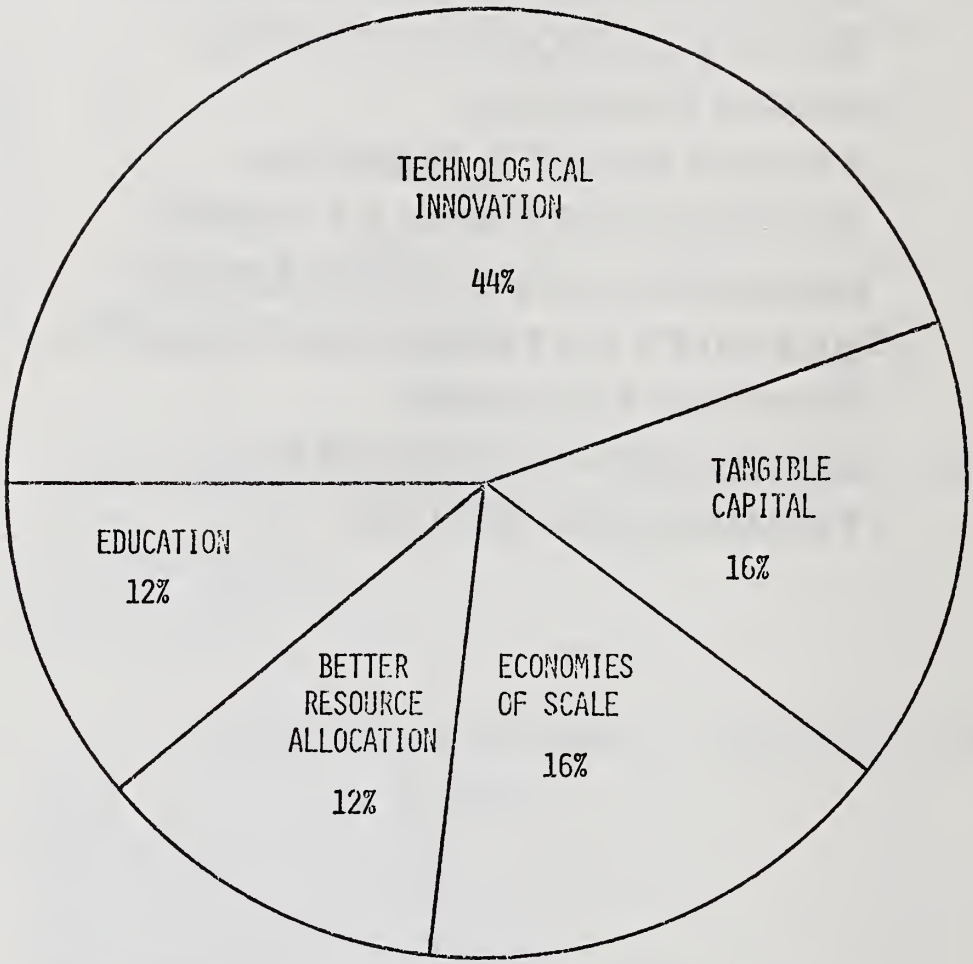

SALARY IMPROVEMENTS
HIGHER SHIFT ALLOWANCES
SHORTER WORKING WEEK
MORE TIME-OFF
FEWER NIGHTS WORKED
MORE WEEK-ENDS AT HOME
GREATER JOB SATISFACTION
DEFINITE FUTURE JOB GROWTH
PROPER TRAINING
MORE RESPONSIBILITY
TECHNICIAN SKILLS

Figure 6

PRIMARY CONTRIBUTORS
TO
IMPROVED PRODUCTIVITY*



* "LABOR" PRODUCTIVITY; RATIO OF MEASURABLE OUTPUT TO INPUT.
SOURCE: BROOKINGS INSTITUTE STUDY -- 1979

Figure 7

AN OVERVIEW OF MAINTENANCE INFORMATION SYSTEMS FUNCTIONS

Victor S. Middlebrook and George D. S. Andrews
Transportation Systems Consulting Corp.
P.O. Box 230 * 5 Sanford Street
Huntington Station, New York 11746

Abstract: Aircraft Maintenance costs are escalating rapidly on practically every front. Maintenance information systems are one of the few areas where costs have remained relatively stable in recent years because computer hardware costs have continued to decrease. This has enabled the development of more cost-effective applications to control costs and manage aircraft maintenance. In this paper a framework of primary maintenance information systems functions is outlined. The list is all-inclusive and covers those functions which interface directly with the aircraft, the powerplant/component/support shops and the management and financial areas. Over fifty different functions are reviewed in some detail to present each potential user with a list he should consider in developing comprehensive maintenance systems. Implementation steps are also discussed and conclusions drawn.

Key words: Aircraft Maintenance Functions; Maintenance Information Systems Functions; Management and Financial Functions; Master Planning; Material and Logistics Functions; Personnel/Component/Support Shop Functions; Power-Plant/Component/Support Shop Functions.

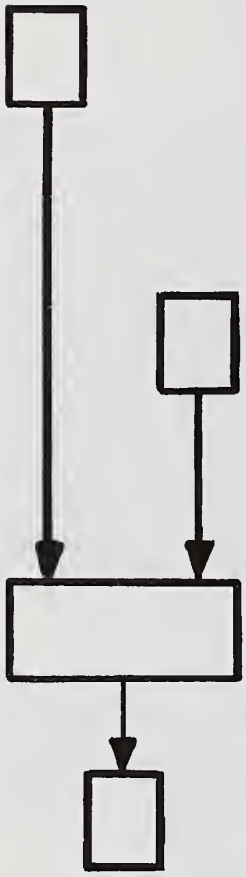
Maintenance Information Systems Functions Overview

It is helpful to have a framework in which to review the Maintenance Information Systems functions. There are a number of approaches to accomplish this. Regardless of which approach is selected there will be individual functions which do not conveniently fit the framework. The framework outline depicted in figure 2 appears to be workable.

The functions are analyzed with respect to their relationship to the aircraft, working away from the aircraft to overall maintenance management costs. The first group of functions to be reviewed are those which interface directly with aircraft maintenance.

AN OVERVIEW OF MAINTENANCE INFORMATION SYSTEMS FUNCTIONS

ABSTRACT



MAINTENANCE COSTS - RISING RAPIDLY:
- LABOR
- MATERIAL
- FACILITIES

MAINTENANCE INFORMATION SYSTEMS COSTS - STABLE
- PROGRAMMING UP MODESTLY BUT
- HARDWARE CONTINUES TO COME DOWN

NET RESULT - INCREASED USE OF MAINTENANCE INFORMATION SYSTEMS (MIS)

THIS PAPER PROVIDES A SHOPPING LIST OF OVER FIFTY MIS FUNCTIONS TO CONSIDER

CAVEATS: EACH FUNCTION MUST BE:
- COST EFFECTIVE
- INTEGRATED
- USER INVOLVED

Figure 1

MAINTENANCE INFORMATION SYSTEMS FUNCTIONS OVERVIEW

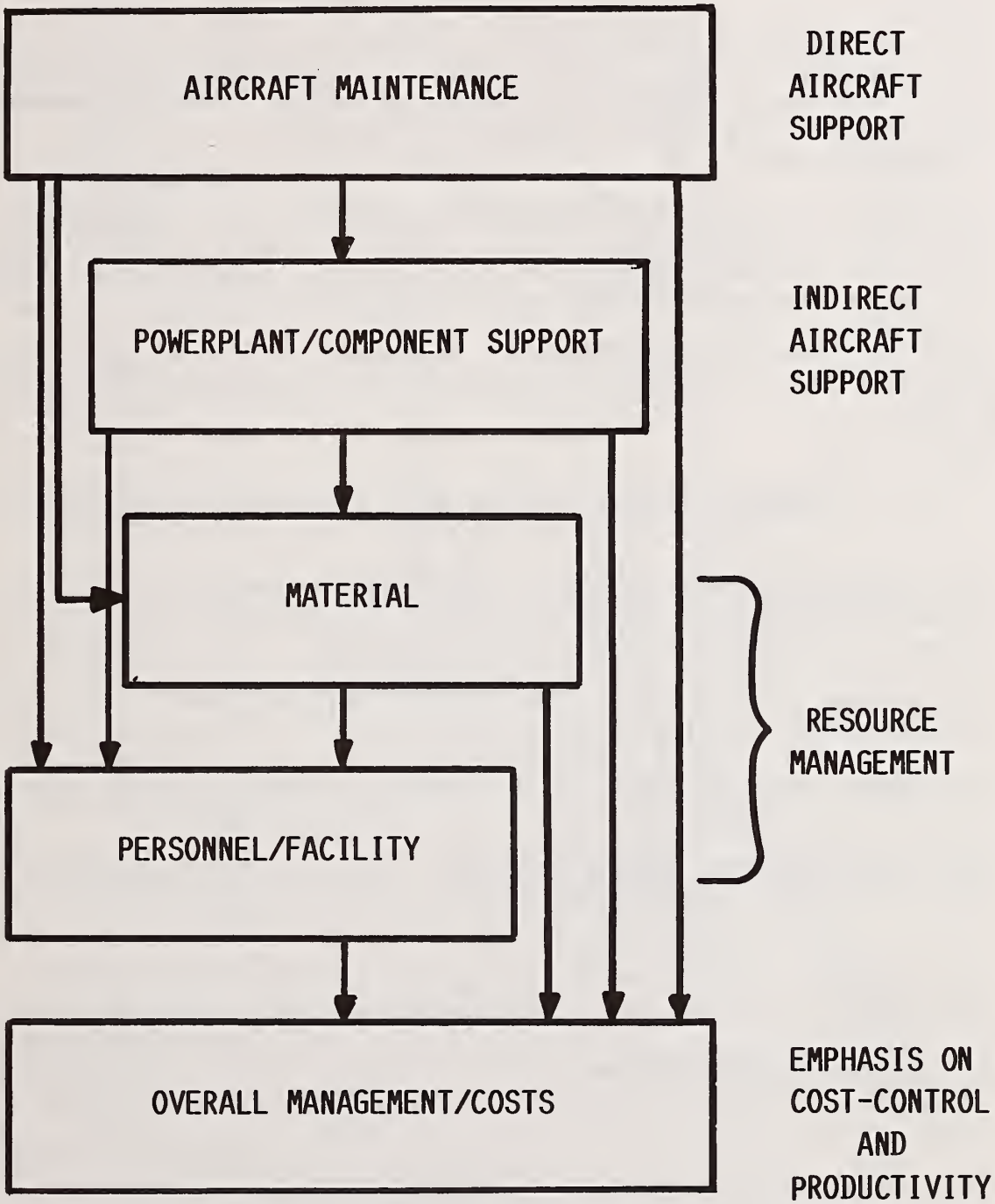


Figure 2

The next set of functions pertain to the powerplant/component/support areas which include all of the shop activities that support an aircraft. This is an area where improved information systems can often reduce costly aircraft delays.

The next group are the material functions which is the next lower support step. If not properly organized, these functions can be a large contributor to delays. The volume of the material processed requires efficient information processing support.

Next are the personnel and facility functions. Personnel is an area, in the decade of the eighties, which will require much more control because of accelerating labor rates. Facility management is just starting to be developed.

Finally, overall maintenance management/costs ties it all together and produces the maintenance organization's bottom line.

Aircraft Direct Maintenance Functions (1 of 2)

A/C Configuration Tracking. Keeps track, for each aircraft, of the powerplant, maintenance units, components, assemblies, and parts presently "hanging on the A/C", by serial number.

A/C Status. Provides the status of pilot reports (pireps), delays, deferrals, previous maintenance actions, etc.

A/C Time. Keeps track of time-on-aircraft in terms of hours, cycles, calendar time, opportunity hours, etc., as appropriate.

A/C Time-When-Due Record Keeping. Compares times on components against allowable times and creates a scheduled maintenance list.

A/C History. Allows maintenance analyst to review any selected tail number, or system, for its maintenance history.

A/C Service Forecasting. Based on reliability history and seasonal A/C requirements, provides a service forecast for a 2 month to 2 year period.

A/C Service Scheduling. Refinement of forecasting function covering 2 days to a 2 month period of time and includes material and personnel requirements.

AIRCRAFT DIRECT MAINTENANCE FUNCTIONS (1 OF 2)

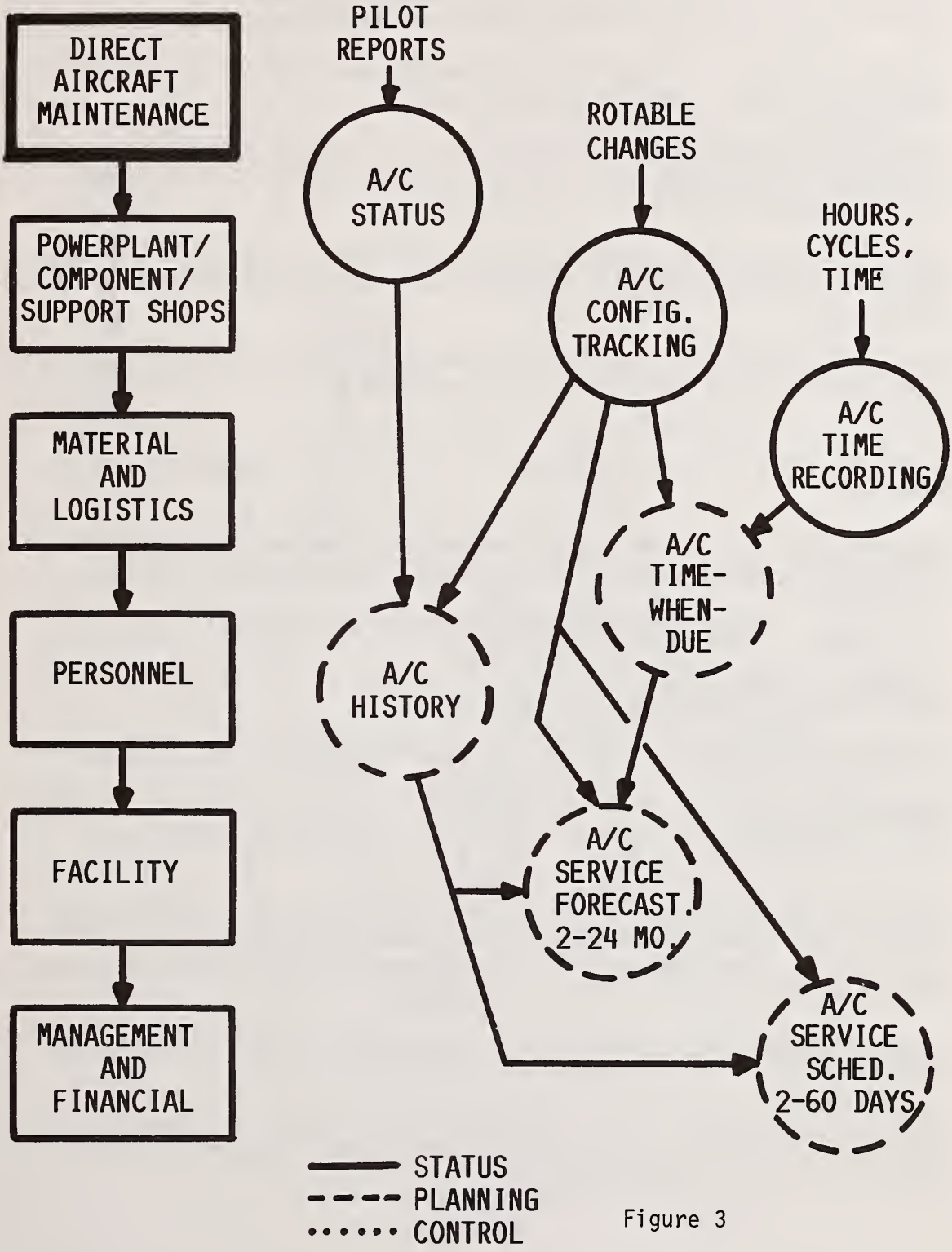


Figure 3

Aircraft Direct Maintenance Functions (2 of 2)

A/C Routing. A real-time operations center function with the ability to redirect aircraft based on maintenance and operational implications.

Work Card Control. A combination of manual and computer work card management (work card index is computerized).

Work Package Generation. Creates a work package for a specific service based on time-when-due, work cards required, modifications planned, servicing required, etc.

Specific Service Work Status. Provides the ability to control heavy services (C & D), integrate inspection generated work, and provide work status.

Modification Control. Provides for control by aircraft and by modification. Allows planning of modifications to be accomplished during a service.

A/C Reliability. Sums up reliability, by aircraft, for monthly fleet reporting.

Warranty Control. Allows the determination of warranty status and provides information for supplier material cost guarantee programs.

Powerplant/Component/Support Shop Functions

Powerplant Forecasting. Provides a 2 month to 2 year forecast of powerplant needs based on A/C requirements.

Component Forecasting. Similar to powerplant forecasting function.

Workshop Forecasting. Provides a 2 month to 2 year forecast of component requirements, by workshop, based on A/C schedule changes and reliability forecasts.

Powerplant Scheduling. Provides scheduling functions for powerplants covering a 2 to 60 day period indicating required powerplants, maintenance units, components, assemblies, and parts based on reliability and A/C schedules.

Component Scheduling. Comparable to powerplant scheduling above, for components.

Workshop Scheduling. Prioritizes workshop schedules for components based on the most critical aircraft needs so that components shops are working on what is most required.

AIRCRAFT DIRECT MAINTENANCE FUNCTIONS (2 OF 2)

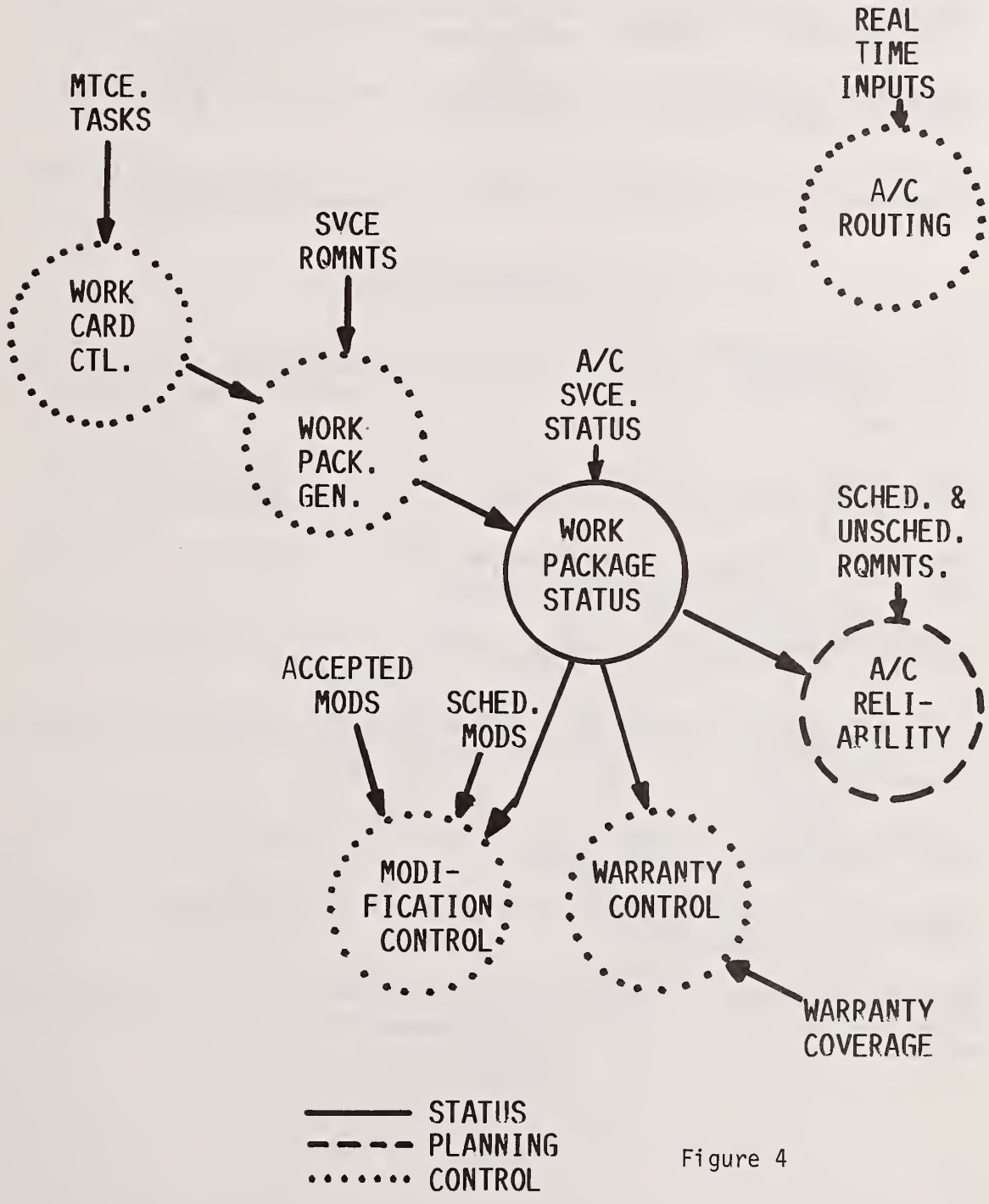


Figure 4

Work Order Generation. Generates on-line work packages that provide complete service instructions.

Support/Service Shop Load Control. Anticipates the magnitude of the load on various machine types, or areas, based on A/C requirements.

Powerplant Tracking/Status. Provides configuration control for powerplants on the A/C comparable and integrated with A/C configuration.

Component Tracking/Status. Comparable to powerplant tracking/status above for components.

Note that there are functions comparable to those in the aircraft area for modifications, warranty and reliability functions.

Material and Logistics Functions (1 of 2)

Parts Identification. This function provides the ability for senior production personnel to identify required components and expendables by part number. A key function is to provide alternate interchangeable part numbers.

Parts Requisition. Companion function to parts identification which allows production personnel to automatically order parts.

Expendables Inventory Status. Provides status function for expendable items by measure rather than by item.

Expendables Consumption (History). Records the issue rate and in turn provides consumption data for planning and purchasing.

Parts Requirements Forecasting. Similar to other forecasting functions covering 2 months to a 2 year period and pertaining primarily to expendables.

Overstock Control. Recognizes overstock situations and provides the basis for surplus sales activities.

Understock Control. Recognizes stockouts and provides the basis for supply level management.

Warranty Management. Provides warranty management control for defective items which are still within the warranty period and guaranteed by the vendor.

POWERPLANT/COMPONENT/SUPPORT SHOP FUNCTIONS

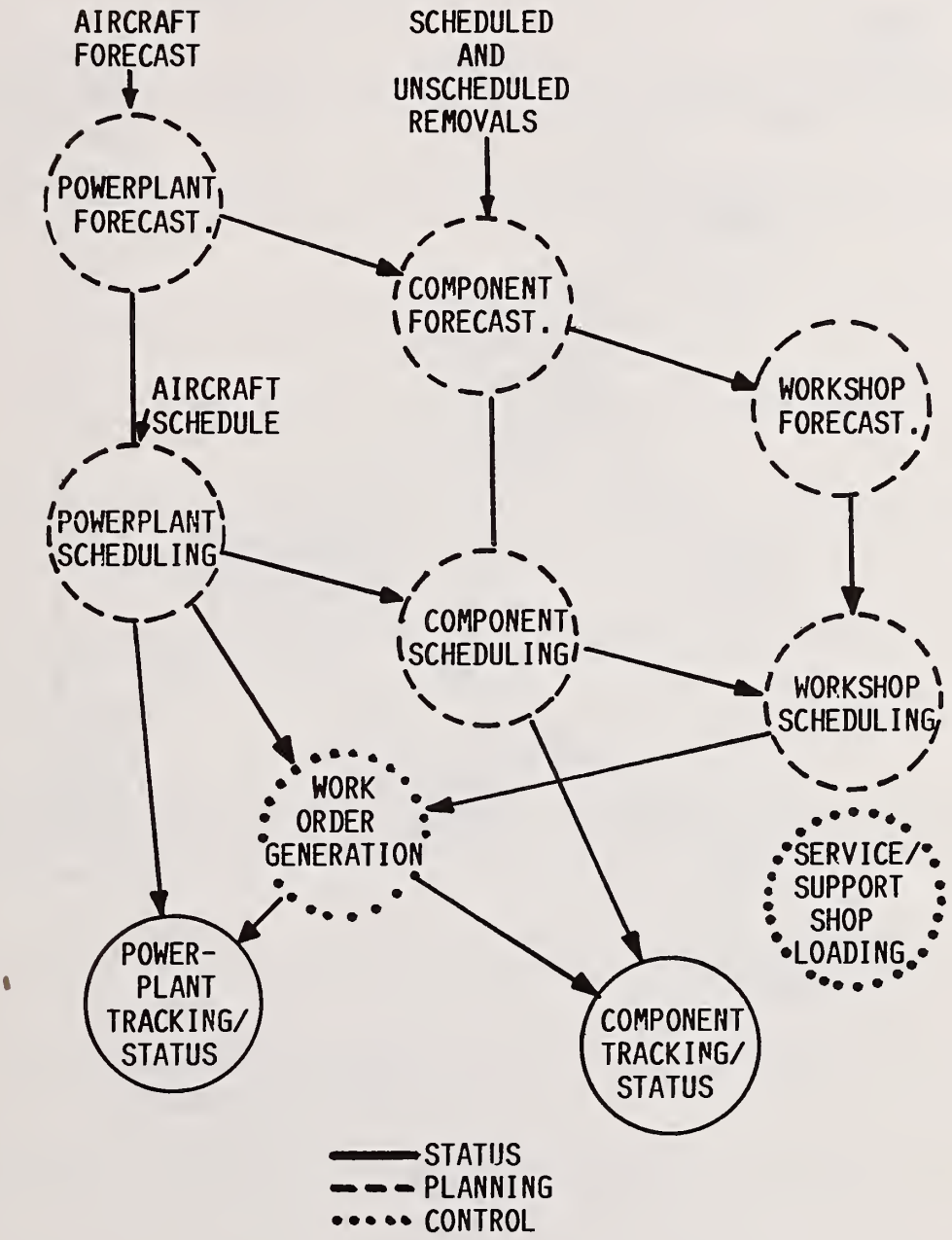


Figure 5

MATERIAL AND LOGISTICS FUNCTIONS (1 OF 2)

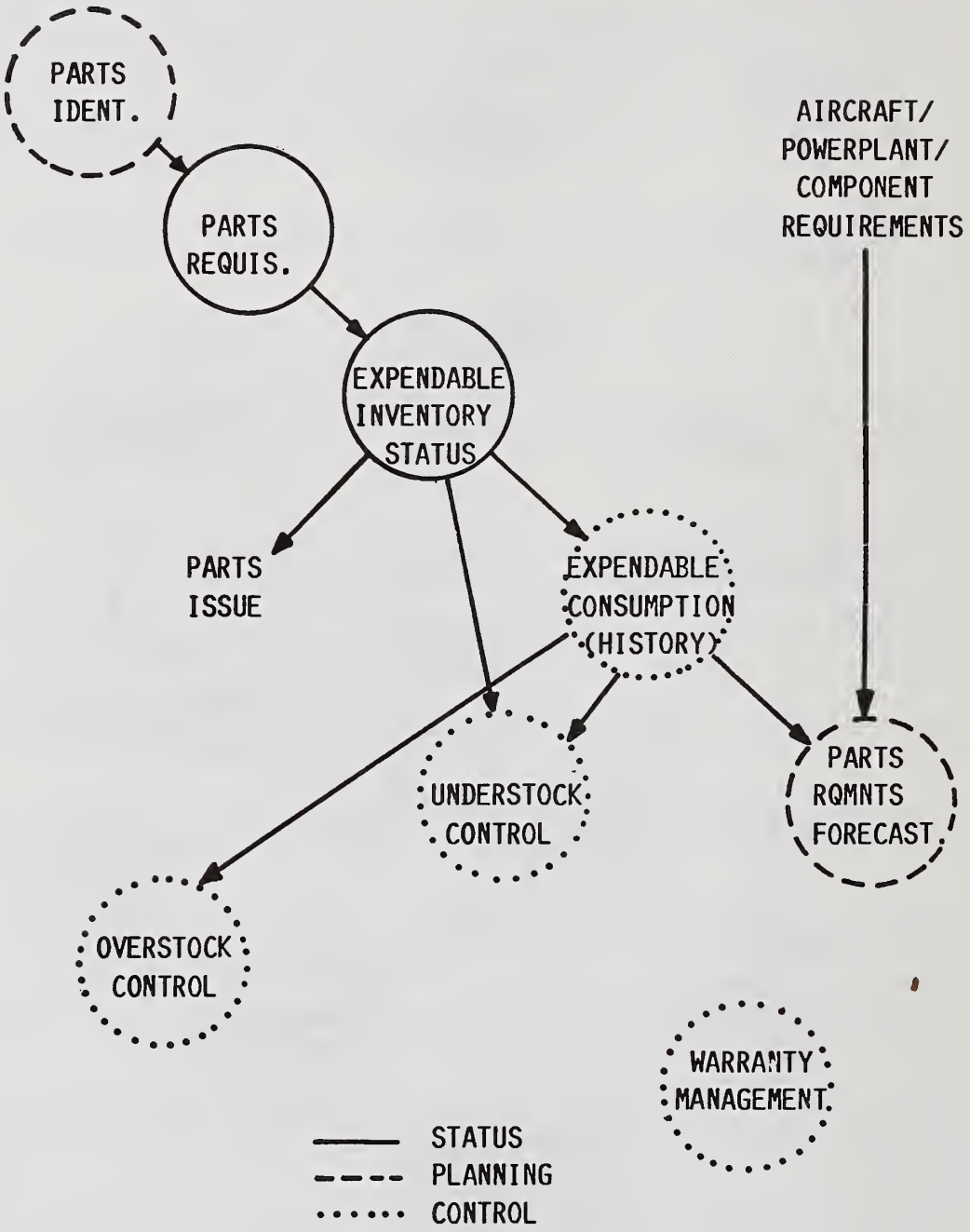


Figure 6

Material and Logistics Functions (2 of 2)

Vendor Control. Keeps track of vendor performance and other critical information required to support purchasing functions.

Purchasing/Ordering. Provides for automatic ordering and generation of purchase orders for certain categories of material. May also have override features to enhance control.

Receiving/Inspection. Provides a convenient method of logging-in received inventory, recording irregularities/short-shipments, beginning status and proof-of-receipt for invoice payment.

Customs Control. Manipulates the shipping and receiving data pertaining to rotables and expendables material so that it is suitable for customs inspection/control.

Shipping Control. Provides shipping data (method, rates, etc.) and tracking information to line stations/vendors.

Line Station Functions. Consideration should be given to real-time tracking of rotables and expendables material issued to line stations.

Material Accounting. Supports accounting functions by listing appropriate inventory as capital items (rotables) and expense items (expendables). Supports perpetual inventory audit.

Spares Provisioning. Provides formula approaches for developing initial support requirements.

Personnel Functions

Personnel Skill Requirements. Provides a forecast of labor requirements based upon aircraft and shop forecasted workloads and historical labor task performance.

Current Personnel Status. Indicates scope of present labor force and near-term availabilities. Can be compared with requirements above.

Labor Reporting. Collects labor statistics by job, during a shift rotation. Produces various management reports concerning productivity, human behavior and overtime status.

Labor Analysis. Analyzes labor expenditures against standards and provides labor productivity information.

Job Costing. Produces total maintenance manpower costs by job function.

MATERIAL AND LOGISTICS FUNCTIONS (2 OF 2)

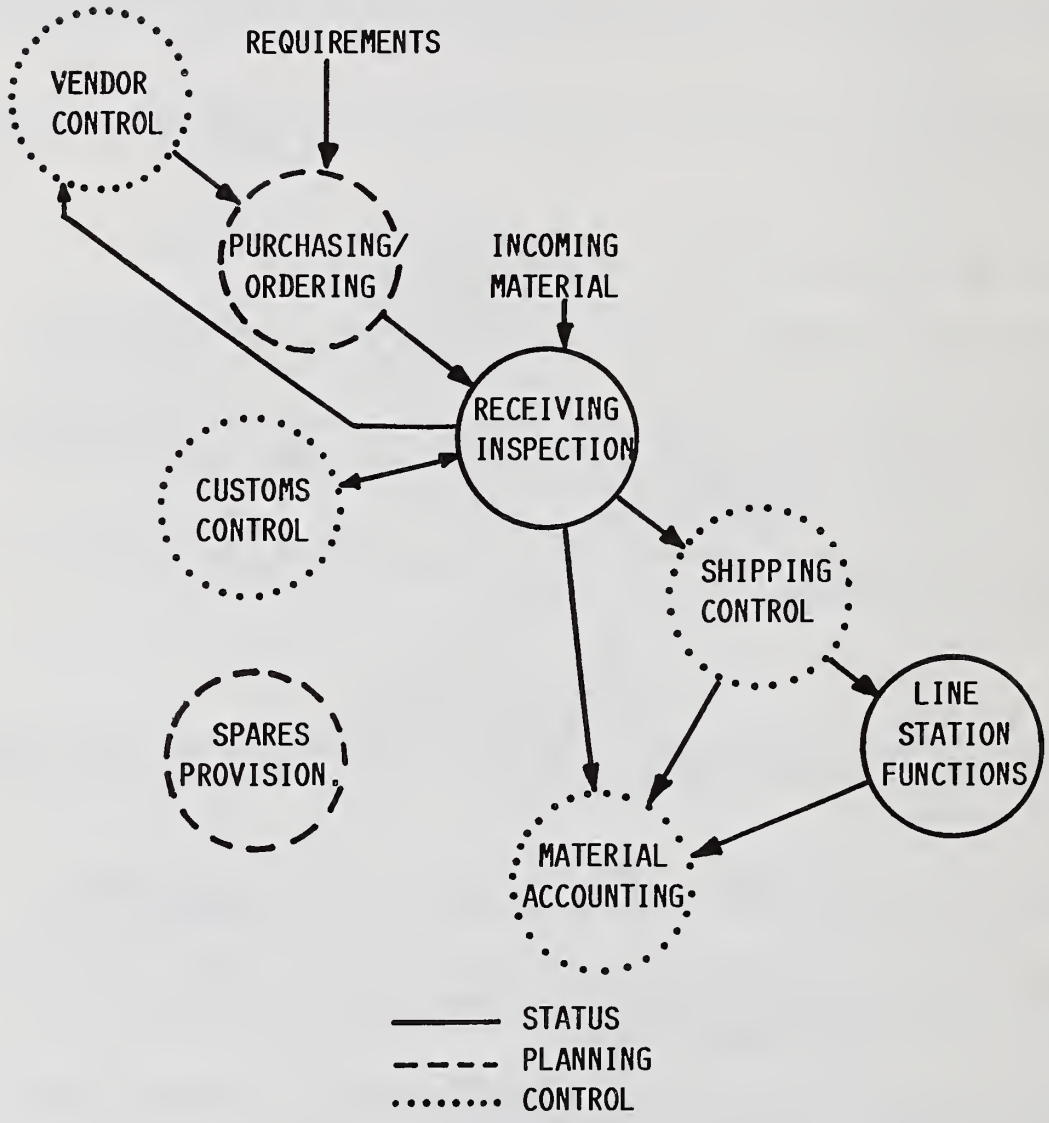


Figure 7

PERSONNEL FUNCTIONS

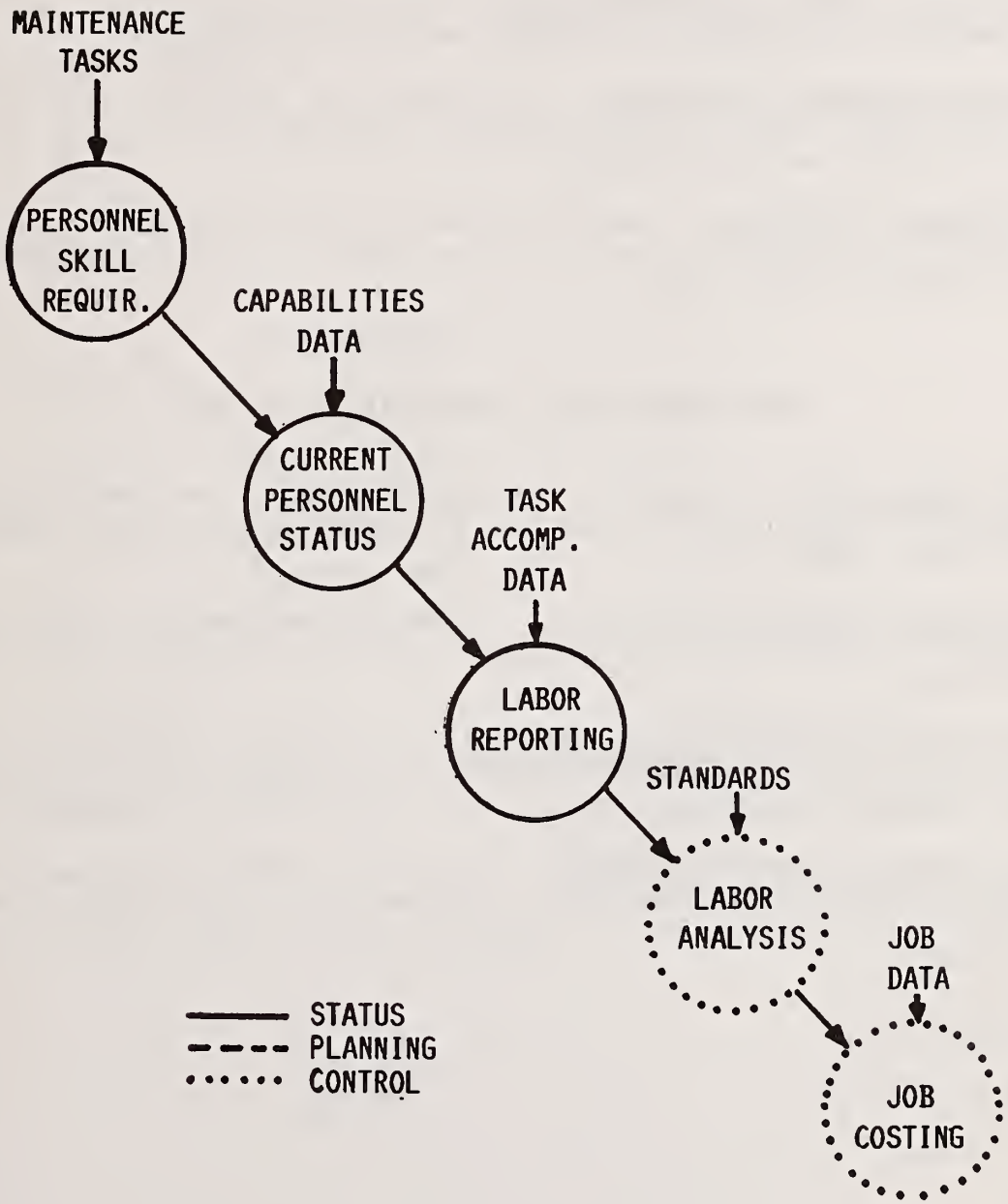


Figure 8

Facility Functions

Facility Status. Provides the location, condition, and assignment of high cost items (payloaders, stands, etc.) which are usually in short supply.

Facility Planning/Scheduling. Provides support for service scheduling and permits a "reservation" function.

Ground Support Equipment. An extensive function in its own right which contains the status, planning and control components described previously.

Container Tracking. Another form of facility for those involved in cargo activities which also has status, planning, and control functions.

Management and Financial Functions

Material Costs Analysis. Collects rotables and expendables material costs by A/C type, by service, and by part number, for cost comparisons.

Personnel Costs Analysis. Collects personnel costs by skill, by A/C type, by service, for cost analysis and comparisons.

Facility/Overhead Costs Analysis. Collects facility costs and provides an analytical figure for monthly cost analysis and overhead costs as a basis for allocating overheads.

Maintenance Costs Analysis. Analyzes total costs based on labor and material costs by A/C type, A/C tail number, service, ATA chapter, etc. Supports third party billing procedures.

FACILITY FUNCTIONS

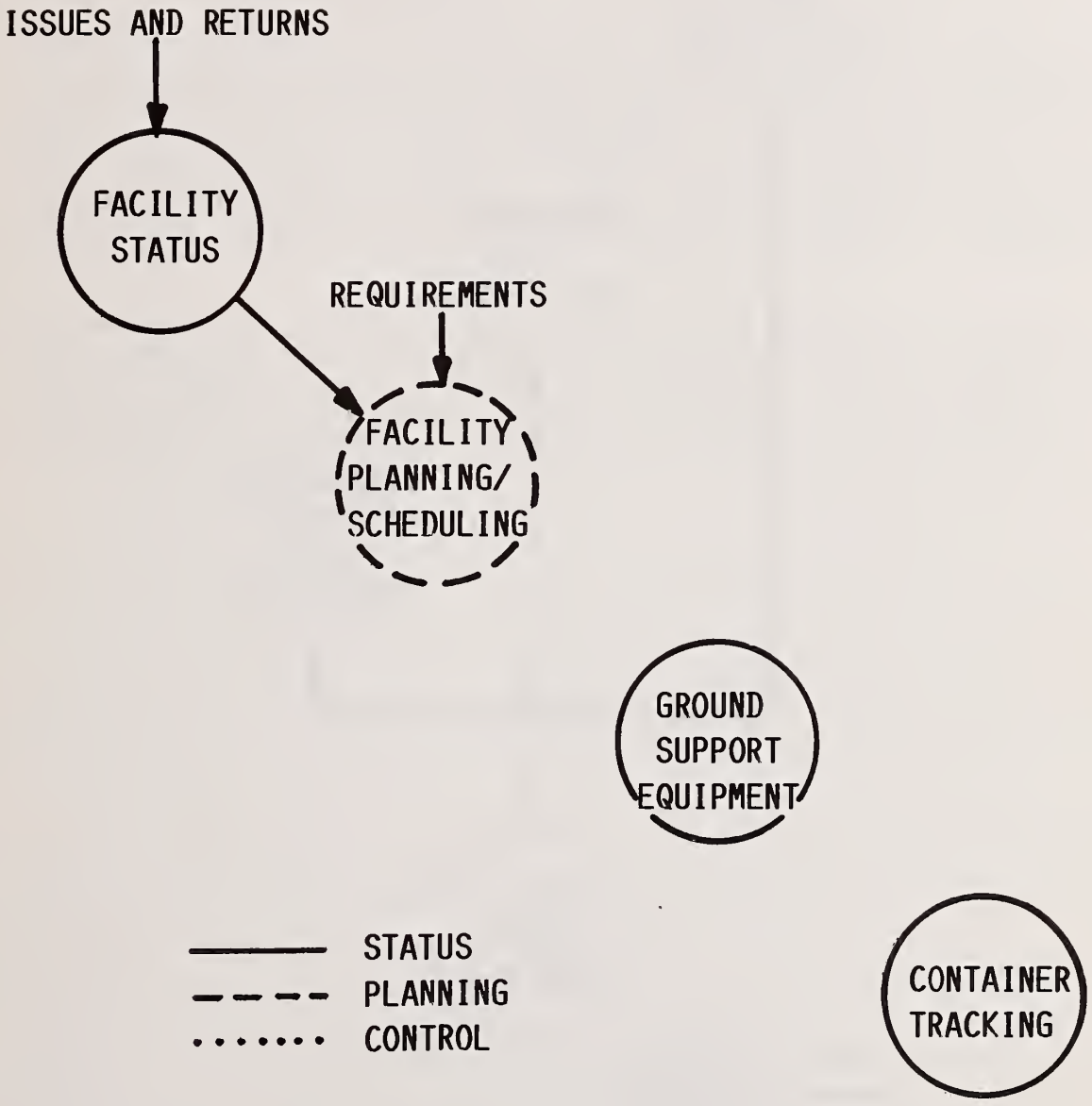


Figure 9

MANAGEMENT AND FINANCIAL FUNCTIONS

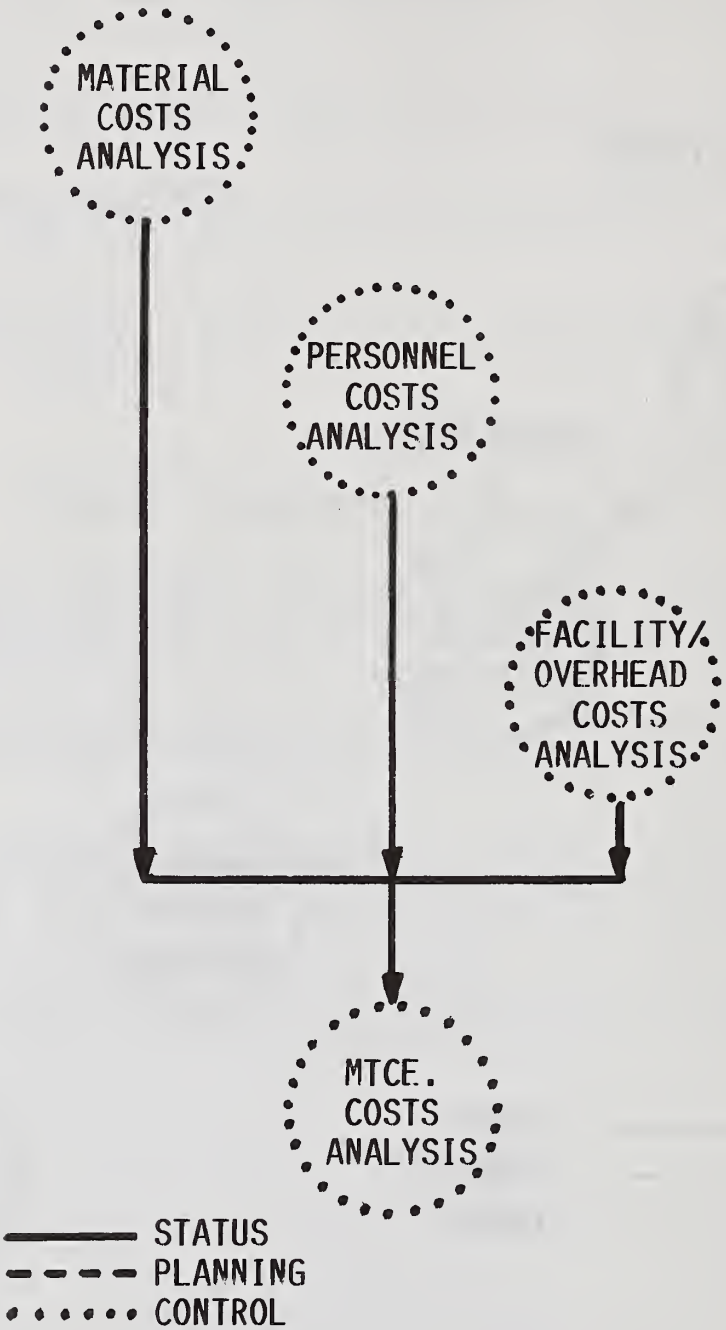


Figure 10

Implementation Steps and Summary

This paper has presented over fifty different maintenance information system functions in six major categories. Each of these functions can be cost effective under the proper circumstances. It is extremely important to appreciate the scope of capabilities in order to select those that are required in your organization.

Figure 11 lists six implementation steps. Master planning is extremely important to prevent major revisions to systems every few years. Each and every effort should start with a feasibility study so that management knows what it is in for. The last step is one we don't spend enough time with and that is system critique. Does the system/module do the job it was designed for and can/should we make it perform better?

Maintenance Information Systems are not a panacea. However, more extensive use of MIS in the maintenance world does offer the opportunity of holding maintenance costs stable in an inflating environment. Effective use of MIS also offers cost efficiency that may not be achievable any other way.

IMPLEMENTATION STEPS AND SUMMARY

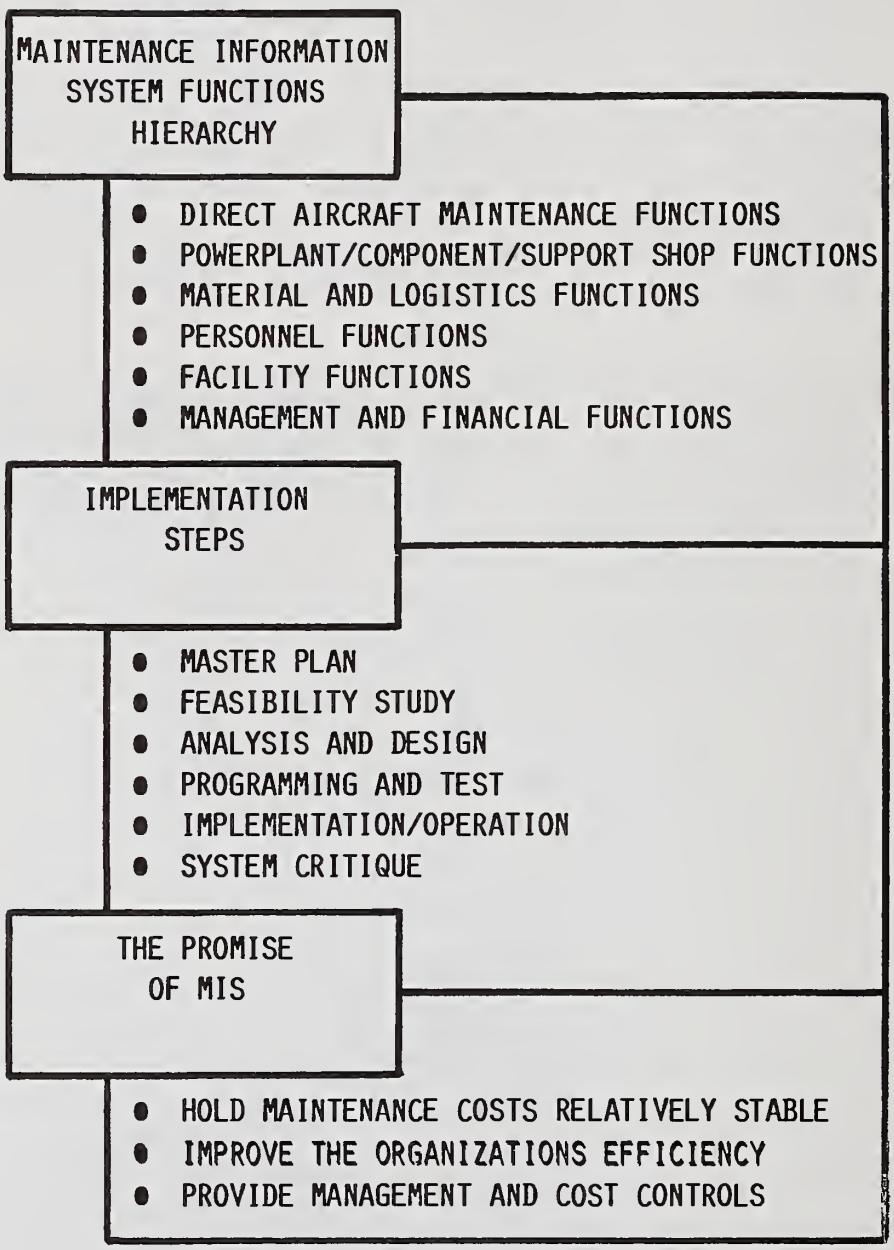


Figure 11

FAILURE MECHANISM AND CAUSE ANALYSIS OF STRUCTURES: A PARADIGM FOR THE ANALYSIS OF FAILURES OR POTENTIAL FAILURES

L. E. Sloter
Vought Corporation
P.O. Box 226144
Dallas, Texas 75266

W. R. Shawver
Vought Corporation
P.O. Box 225907
Dallas, Texas 75265

D. J. White
Vought Corporation
P.O. Box 225907
Dallas, Texas 75265

A novel heuristic failure analysis procedure that incorporates multidisciplinary considerations within a constructive framework to aid in the analysis of actual engineering failures or the failure potential of structures is described and discussed. The Failure Mechanism and Cause Analysis (FMCA) procedure disassembles a failure process into its component parts such that the overall process may be analyzed more easily. From such a breakdown the sources or causes of an actual failure may be more effectively determined or the most probable potential failure processes identified. Once an overall failure process, either actual or potential, has been defined and understood, remedial or preventive action may be taken more effectively. Such action may include redesign, stricter quality control, a maintenance task, or a combination of these things.

Key Words: Engineering failure mode; failure; failure analysis; Failure Modes and Effects Analysis; maintenance (inspection) interval

1.0 INTRODUCTION

The failure analysis procedure reported herein was developed during the execution of a program that had been designed to create a methodology for the determination of structural maintenance intervals for U.S. Navy aircraft on the basis of calculated safety-of-flight risk criteria. In particular, the overall methodology had been required to realistically address the complete process of structural degradation

and to provide a quantitative rationale for structural maintenance intervals based on a statistical analysis of failure mechanisms, failure rates, and inspection capabilities.

1.1 METHODOLOGY OVERVIEW

The method, in order to be as comprehensive as possible, models the entire process that an aircraft item would see in its lifetime, that is from design through manufacturing to flight operations and inspections. The method allows for the use of the latest state-of-the-art analytical techniques where possible and proposes new or modified techniques where necessary. The basic methodology for determining maintenance intervals is illustrated in flowchart form in Figure 1. It consists of two major analytical sections that are effected after those critical items requiring analysis are identified. These sections are briefly the following:

(1) Damage Identification - Analyze potential failure processes for each item, paying particular attention to corrosion and crack, especially fatigue-crack, initiation.

(2) Damage Rate Analysis - Conduct probabilistic damage rate analyses for both corrosion and fatigue using appropriate load spectra and environments. Two calculational sections are applied following the kinetic analysis as follows:

(a) Assess Risk - Predict failure probabilities from the joint probability density function of critical crack sizes and predicted crack growth.

(b) Schedule Maintenance - Determine maintenance intervals considering non-destructive inspection capabilities and safety (risk). Recalculate failure probabilites in light of the scheduled maintenance and repair and redetermine intervals if necessary.

The methodology thus consists of two primary analytical activites - the Failure Mechanism and Cause Analysis (FMCA) and the Damage Rate Analysis (DRA). The former technique is a logical framework developed in order to provide a definitive procedure for analyzing the failure potential of items and a means for reporting the results of such an analysis. It should be considered as a definitive means whereby an analyst may perform an analysis of the potential failure process to which an item may be susceptible, divide that process into analyzable components, and convey the analytical results for purposes of decision making or further kinetic analysis. The kinetic analysis developed for this purpose is the Damage Rate Analysis procedure incorporated in the overall structural maintenance methodology. The details of the DRA as well as an example of the overall implementation of the structural maintenance methodology have been reported, by Shawver, et al[1]. The present discussion is limited to the failure analysis procedure (FMCA) developed for the methodology.

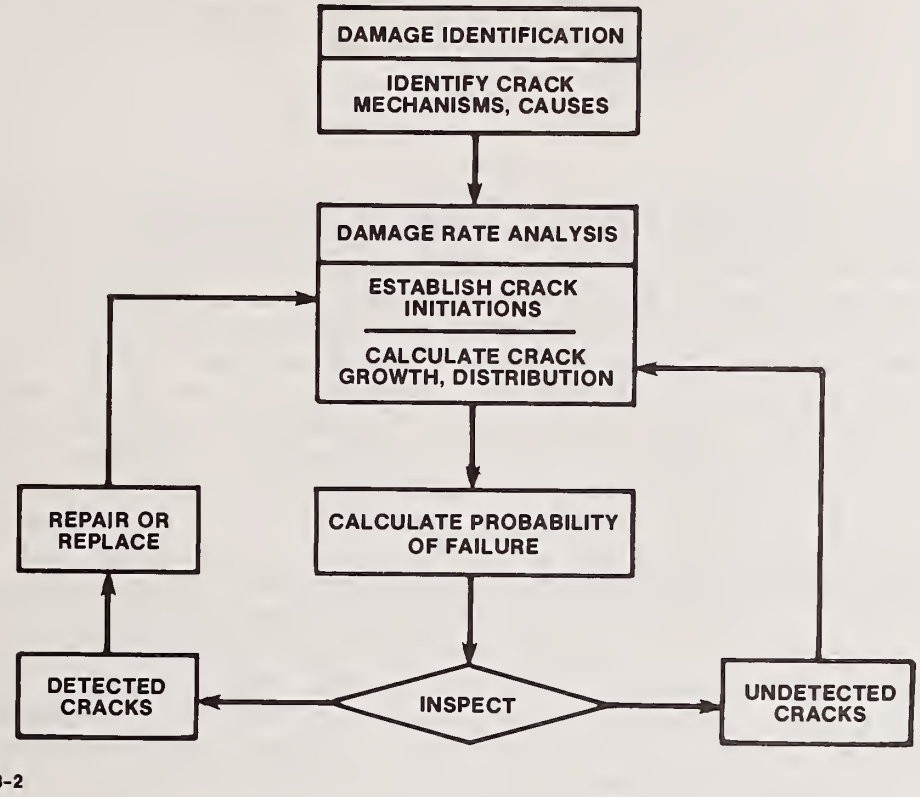


FIGURE 1: STRUCTURAL MAINTENANCE INTERVAL METHODOLOGY-SCHEMATIC PROCESS OVERVIEW.[1]

2.0 FAILURE MECHANISM AND CAUSE ANALYSIS

2.1 BACKGROUND

Failure Mechanism and Cause Analysis (FMCA) is a logical framework developed to assist the designer, failure analyst, maintenance engineer, or other interested party in the evaluation of the potential failures inherent in a product design and the paths by which failure could occur or in the evaluation of the possible causes of a particular failure under analysis.

2.2 ORIGIN

Failure Mechanism and Cause Analysis has its origins in the general techniques of Preliminary Hazards Analysis[2]; Failure Mode and Effect Analysis[2,3,4]; Failure Modes, Effects, and Criticality Analysis[2,3,4]; Decision Tree Analysis[2]; and Maintenance Plan Analysis[5,6] as well as the general engineering disciplines of failure

analysis and risk analysis. Although the FMCA technique is derived from these other areas and bears a strong resemblance to them in parts, its purpose, uses, and procedures are sufficiently distinct that it is uniquely named and should be considered to be a unique and individual analysis technique.

2.3 FMCA AND FMEA

The principal difference between the Failure Mechanism and Cause Analysis (FMCA) and the classical Failure Mode and Effect Analysis (FMEA) is that the latter mainly examines functional failure modes while the former examines essentially engineering failure modes (Figure 2). It cannot be emphasized too strongly that functional and engineering failure modes are distinctly different, albeit related things. FMEA's usually begin with the functional failure mode and examine its effect on system operation. FMCA's begin with the engineering failure mode responsible for the functional failure and examine the failure mechanisms and sources which had led to or caused the occurrence of the engineering failure mode for purposes of preventing the failure from recurring. The FMCA may also begin with the failure mechanisms and sources and examine the potential for the occurrence of an engineering failure mode for purposes of designing or maintaining against the occurrence of the failure. In either case, actual engineering failure mode or potential engineering failure mode, the FMCA may also consider the failure effect or effects of the identified failure. In summary, then, the FMCA is an engineering analysis. The FMEA, on the other hand, is principally a systems approach to failure and failure effect. Generally, beginning with a functional failure mode, the FMEA examines the effect of that failure on system reliability or effectiveness for the purpose of minimizing the consequences of failure through fail-safe design, redundant design, or failure tolerant design. The FMEA and its more general progenitor, the Preliminary Hazards Analysis, are principally systems analysis and design techniques, not engineering failure analysis tools.

3.0 FAILURE MECHANISM AND CAUSE ANALYSIS METHODS

3.1 PURPOSE

Failure analysis encompasses a variety of systematic and logical methods and procedures which may be applied to failures which have occurred in testing or in service or which potentially may occur. A hypothetical failure analysis may also be performed by a designer or other person to discern potential weaknesses or failure possibilities in a design. Most often, however, failure analyses are undertaken following an actual failure, although the failure may have occurred in testing and not in actual service.

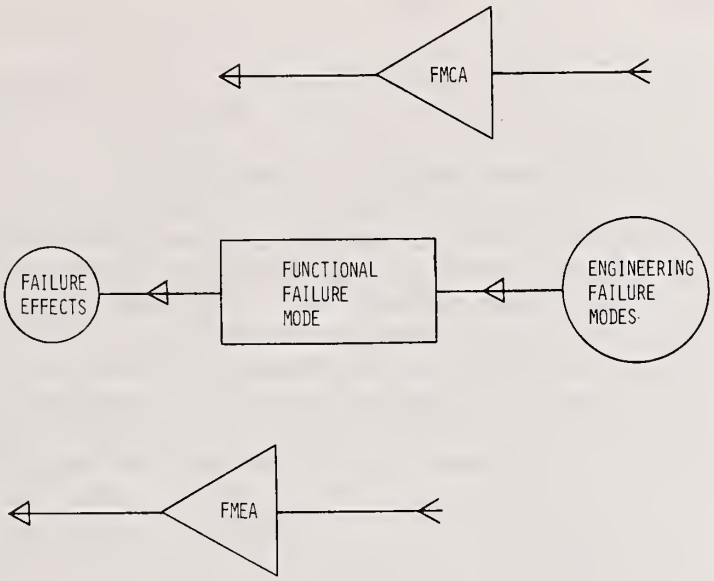


FIGURE 2: FAILURE MECHANISM AND CAUSE ANALYSIS AND FAILURE MODES AND EFFECTS ANALYSIS CONTRASTED.

3.2 GOALS

In general, it is good practice to explicitly state the purpose or goal of the analysis initially so that misunderstandings are avoided and the proper analyst for the specific job is chosen. The goals of a failure analyst or the purposes of an individual failure analysis are not always the same or even compatible. Some failure analyses are conducted in order to determine a fix which will prevent a similar failure from occurring. Such a fix may be a design change, material substitution or modification, a change in environment, or some other alteration. Other failure analyses are performed in order to determine the cause of failure or the most basic action, event, mechanism, or source without which there would have been no failure. Analogous to this goal may be an interest on the part of the failure analyst to understand the fundamentals of a failure process. Finally, a failure analysis may be conducted primarily for the purpose of assessing responsibility or blame for a failure. This responsibility may be laid upon the designer, the manufacturer, the repairer, the user, some other party, or any combination of these persons. In order to assess blame in such an analysis, cause must usually be determined such that some party, the responsible party, had control of or could have prevented the cause. Often these failure analysis goals lead to incompatibility among the opinions and conclusions of the analysts.

3.3 THE ANALYST

In addition to variability in analysis goals, various persons may be assigned the task of performing a failure analysis. The analyst may be an inspector or repairman who discoveres an unusual circumstance and performs a brief failure analysis to determine if the occurrence should be reported, more closely inspected, repaired, or ignored. A maintenance engineer may often act as failure analyst in order to determine if a maintenance task may be effective in preventing or postponing failure. On occasion, failures of sufficient importance or magnitude will occasion the services of professional failure analysts. Such persons will often be mechanical or structural engineers, materials engineers, specific product engineers, other engineering specialists, or teams of such individuals. In any given instance of failure, a decision must be made at the beginning with respect to the necessary level of the analysis and the personnel required. Such a decision will set the goals of the analysis and generally the depth to which it will be conducted. Of course, during the analysis process, the analysis may be expanded or limited in order to efficiently meet changing goals or react to additional information.

In general, it should be noted that failure analyses are usually conducted under the auspices of someone other than the failure analyst himself. This responsible authority will generally decide that an analysis will be performed, who will perform it, and what the level or depth of the analysis will be. This authority should become sufficiently familiar with the failure, the techniques of failure analysis, and the potential causes of failure so that he can effectively make the necessary decisions.

3.4 TECHNIQUES

The specific experimental and analytical techniques employed in failure analysis are potentially and virtually all the experimental techniques employed in engineering and science in the broadest sense. The language of failure analysis includes terms from most engineering disciplines as well as terms specific to itself. For these reasons, no brief discussion can effectively document or cover the "fields" of failure and failure analysis. These areas, therefore, must be broken up into concisely explicable parts.

The following sections present a discussion of a logical technique which can aid the failure analyst in the examination of a failure by presenting him with a framework wherein failure potentialities may be discerned or placed. Furthermore, this framework or Failure Mechanisms and Cause Analysis may aid the designer in detecting specific, potential failure processes in items. In this respect the FMCA is complementary to a Failure Mode and Effect Analysis which may also be specified in the design stage of an item. Finally, the FMCA is used to disassemble a failure process into analyzable parts such that Dam-

age Rate Analysis may be applied in order to predict failure or define the risk of failure with time.

3.5 FMCA METHODOLOGY

The path which leads to failure is often a very twisted and non-direct one made up of unlikely events, unconsidered driving forces, and interactive occurrences. When only the cause of failure is to be determined, then it is only necessary to examine the specific chain of events which could lead to an individual failure. When a failure is to be more fully analyzed, however, these individual events must be sorted and defined for individual analysis and interactions must be considered. Such an analysis may be termed a "Potential Failure Analysis" and is outlined as follows using the Failure Mechanism and Cause Analysis terminology (also See Figure 3):

FMCA: POTENTIAL FAILURE ANALYSIS OUTLINE

I. Identify and carefully describe the item to be analyzed.

A. Describe the function of the item.

B. Describe the physical characteristics of the item.

II. Identify and describe the intended environment in which the item is to be used and the time or time related parameter associated with the environment.

A. Include.

1. Physical environment.

2. Mechanical environment.

3. Chemical environment.

4. Functional environment.

B. Evaluate the probability of changes or additions to the use environment and possible environmental interactions with other items.

III. Identify and list the potential primary engineering failure modes to which the items may be susceptible.

A. Examples.

1. A structural item may be susceptible to fracture.

2. A rotating item may be susceptible to seizure and fracture.

3. A semiconductor device may be susceptible to fracture (of leads or case) and to thermal failure.

B. Estimate the level of severity of each engineering failure mode.

IV. Identify and list the driving forces to which the item is subjected in its environment.

V. Identify and list the failure mechanisms and sub-mechanisms which could lead to a given engineering failure mode in the use environment under the identified driving forces.

A. Determine the probable failure mechanisms and sub-mechanisms.

VI. List the failure sources and sub-sources which could lead to the probable failure mechanisms or to the engineering failure mode.

A. Determine the probable failure sources and sub-sources.

VII. Determine the most probable cause(s) of failure for each engineering failure mode.

VIII. Estimate the overall probability of each engineering failure mode.

IX. Determine if secondary engineering failure modes are possible and if their severity requires further analysis.

A. If such analysis is required, repeat steps III through VIII for the secondary engineering failure modes.

X. Determine the necessary actions required to prevent those engineering failure modes which are intolerable.

In the performance of the above failure analysis scheme, the construction of a failure tree may be of use. Such a construction also may be of use in presenting in a graphical format the results of a potential failure analysis. The failure tree itself is a graphical construction, similar to a decision tree[2,5] that illustrates failure mechanisms, sub-mechanisms, sources, sub-sources, and their relationship to one another. Driving forces may be shown below failure mechanisms and sub-mechanisms and other notations may be contained on the tree. Although the discussion of the analysis methods contained herein begins or ends with an identified engineering failure mode not a failure effect, the logical completion of a potential failure analysis will often require consideration of failure effects. Nevertheless, in this regard, it often may be preferable to consider the functional failure mode which corresponds to an engineering failure mode and perform a

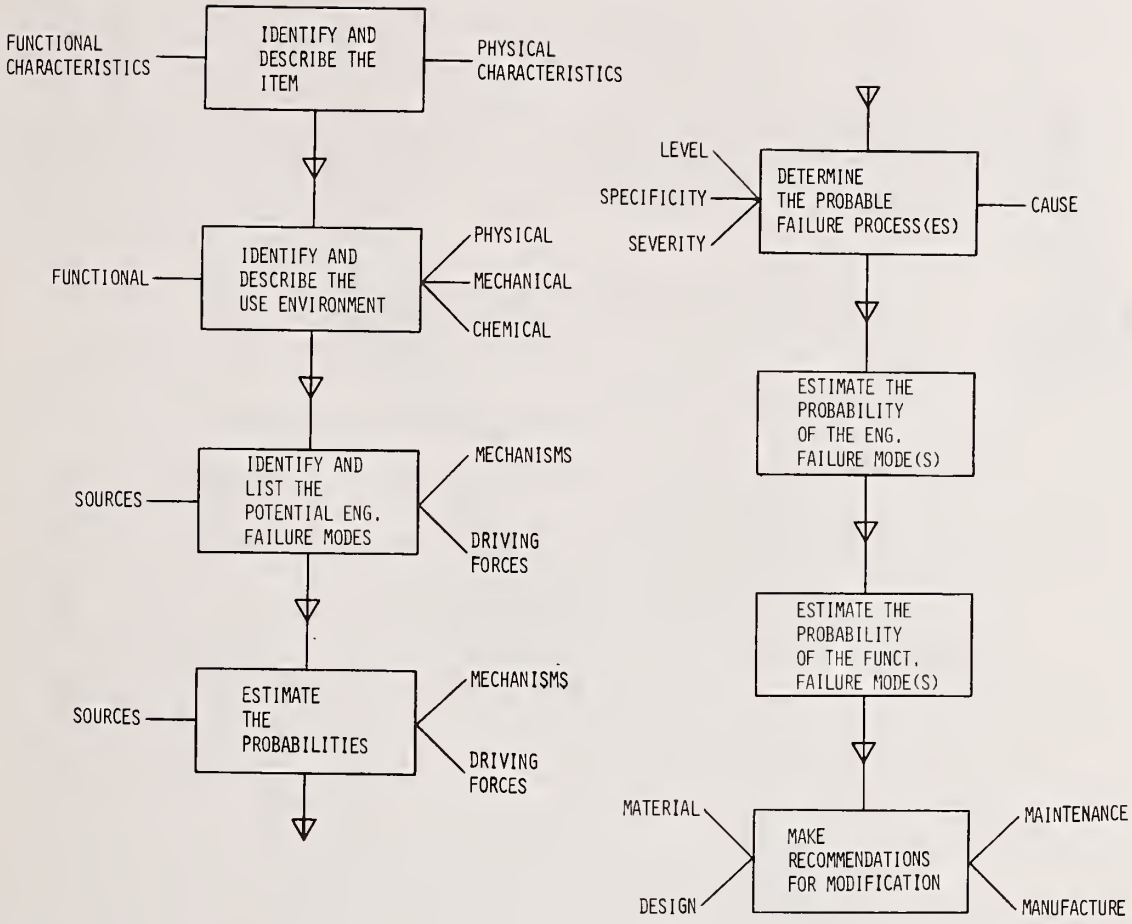


FIGURE 3: FMCA POTENTIAL FAILURE ANALYSIS OUTLINE.

Failure Mode and Effect Analysis in order to determine the failure effect. It will often prove necessary and difficult to analyze the relationship of engineering failure modes and a failure effect in order to determine the level of each engineering failure mode or potential engineering failure mode. When functional failure modes and effects are most important to the analysis, then the suggested analysis technique would be Failure Mode and Effect Analysis. Also see Figure 4.

In addition to the performance of a potential failure analysis, the FMCA methodology is amenable to the performance of a failure analysis of an item that has actually failed in service. It may aid the analyst in logically and systematically disassembling the failure

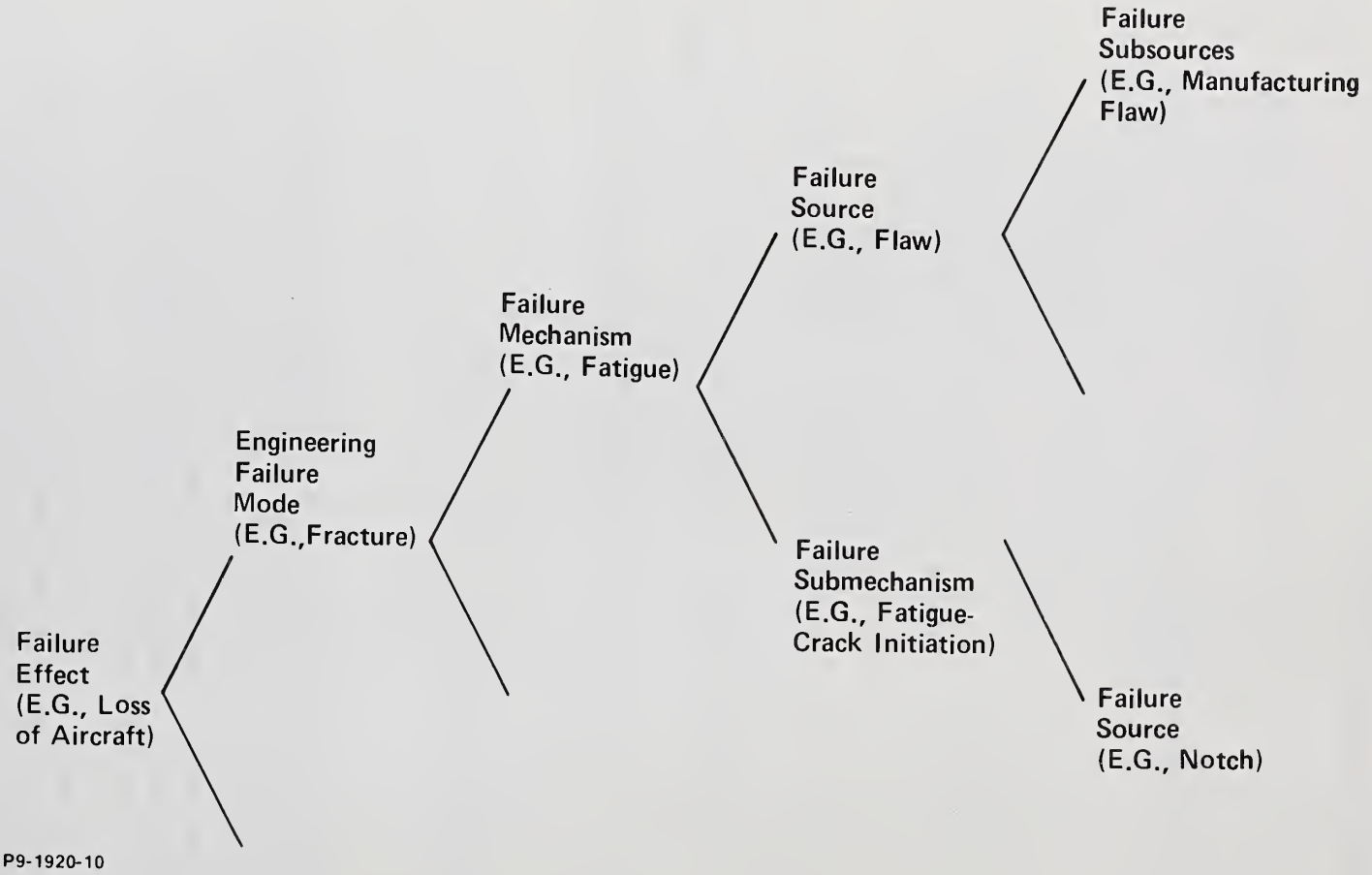


FIGURE 4: FMCA FAILURE TREE SCHEMATIC.

process into its most probable parts. When only the cause of failure is to be determined, then it is only necessary to examine the specific chain of events which led to an individual failure. When a failure is to be more fully analyzed, however, these individual events must be sorted and defined for individual analysis and interactions must be considered. The following, then, is an outline of a failure analysis within the overall framework of Failure Mechanism and Cause Analysis (also see Figure 5):

FMCA: FAILURE ANALYSIS OUTLINE

I. Examine the overall failure.

A. Examine the failed item.

B. Examine the history of the failed item.

C. Determine the designed and actual environment of item use.

II. Identify the engineering failure mode(s).

A. Examples.

1. Fracture.

2. Seizure.

3. Elastic failure.

4. Plastic failure.

5. Thermal failure.

III. Identify the potential failure mechanisms, sub-mechanisms, and driving forces which could lead to the identified engineering failure mode(s).

A. Estimate the probability of each failure mechanism and sub-mechanism.

B. Identify the probable failure mechanisms and driving forces.

IV. Identify the potential failure sources and sub-sources.

A. Estimate the probability of each failure source and sub-source.

B. Identify the probable failure sources and sub-sources.

V. Determine the severity of the engineering failure mode(s).

VI. Determine the most probable mechanisms, sub-mechanisms, sources, and sub-sources, as well as the most probable driving forces which could lead to the identified engineering failure mode(s).

A. From the above information determine the most probable failure process(es).

VII. Estimate the probability of the engineering failure mode(s) and the functional failure mode.

VIII. Determine the level of the engineering failure mode(s).

A. Primary failures.

B. Secondary failures.

IX. Determine the cause(s) of failure.

A. Primary failures will have mechanisms or sources as causes. Sub-mechanisms and sub-sources may, of course, also be causes.

B. Secondary failures will have a primary failure as a cause.

X. Determine if the engineering failure modes are generic or specific.

A. Examples.

1. Primary fatigue failures are usually generic.

2. A seizure caused by a unique instance in which lubrication was not performed is a specific failure.

3. A seizure caused by the failure of a specified lubricant is a generic failure.

4. The plastic failure of a link caused by a wheels-up landing is a specific failure.

XI. If the analysis calls for it, assess various methods for preventing the same or similar engineering failure modes in the future.

A. Often secondary failures will require no action, since they may be prevented by preventing the primary failure. Of course, a more reliable system may result if a modification is made to independently prevent a secondary failure.

B. The above often also may apply to specific failures.

C. Modifications which may be made to prevent failures include modifications in:

1. Design,

2. Material,

3. Maintenance, and

4. Manufacture.

D. Recommendations for failure prevention should be accomplished by sufficient analysis and justification to show the efficacy of the proposed change.

A partial failure tree constructed to illustrate the technique for the structural failure of aircraft by fracture is illustrated in an addendum. This failure tree is not intended to be rigorously complete or definitive, but rather to be sufficiently detailed and inclusive so that the requisite parts of the failure tree are illustrated. In addition, the tree has been constructed such that it may be used as an example both overall for other failure trees and in detail for structural fatigue fractures. An attempt has been made to be as technically correct and precise as is possible in the construction of a general failure tree.

4.0 SUMMARY

The performance of failure analysis - either of items that have failed in service or for the purpose of determining the ways an item could fail in service - is an integral part of both product performance and safety analysis as well as product design and redesign. Although each product and each product failure are unique, there are many facets of commonality respectively among them. In particular, the inductive or deductive sequence of a failure analysis or poential failure analysis is not greatly product or event specific. Many considerations, such as usage environment and careful item description including secondary functions, should be included in any failure analysis of a product. Finally, due to the fact that failure analyses are performed by multidisciplinary means, it is extremely important that precise language be used to describe failure or potential failure and to convey the information and conclusions obtained during the analysis. This may require an almost forensic attention to the semantic details of a failure analysis report.

The procedures presented herein are intended to aid in the conducting and reporting of a failure analysis and have been devised to achieve the above analytical requirements. In addition, the FMCA methodology

is intended to be an integral part of a larger methodology that examines the kinetics of identified failure processes such that an estimate may be made of failure probabilities for purposes of lifetime estimation or maintenance scheduling.

5.0 ACKNOWLEDGEMENT

The Maintenance Intervals for Aircraft Structures Methodology development was conducted by Vought Corporation for the Naval Air Systems Command, Washington, DC under CMES Task LTV-79-12. The program contract monitor was Mr. George Donovan, Naval Air Systems Command, Maintenance Policy and Engineering Division, Aircraft Structures and Equipment Branch, AIR 4114.

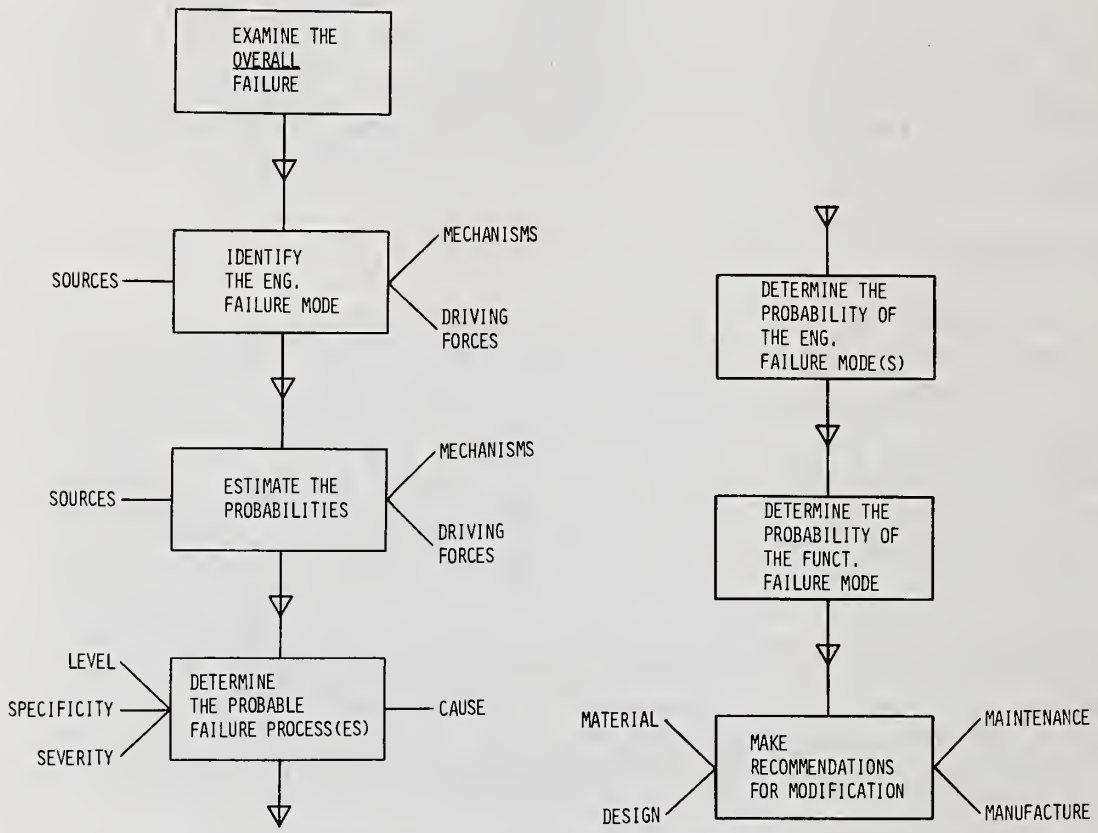


FIGURE 5: FMCA FAILURE ANALYSIS OUTLINE.

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ADDENDUM: FAILURE MECHANISM AND CAUSE ANALYSIS-FAILURE TREE

KEY

P Analytical Aspects of Failure Mechanisms

1. Deterministic
2. Probabilistic
3. Potentially either deterministic or probabilistic

Q Analytical Aspects of Failure Sources

1. Deterministic
2. Probabilistic
3. Potentially either deterministic or probabilistic

I Locations at which Inspection May Alter or Arrest Path or Process

D Locations at which Design May Have a Beneficial Effect

1. Structural design
2. Material selection or design

M Location at which Fabrication May Have an Effect (Fabrication Refers to Assembly and any Reassembly)

R Locations at which Maintenance May have a Beneficial Effect

FAILURE MECHANISM AND CAUSE ANALYSIS:
FAILURE TREE - STRUCTURAL FAILURE

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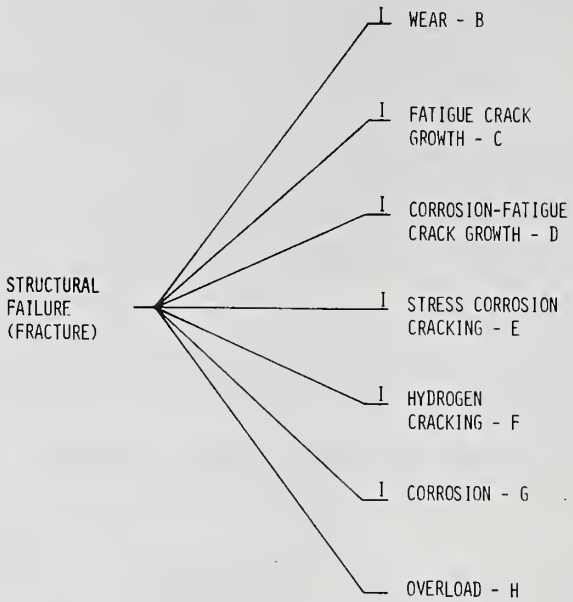

FMCA

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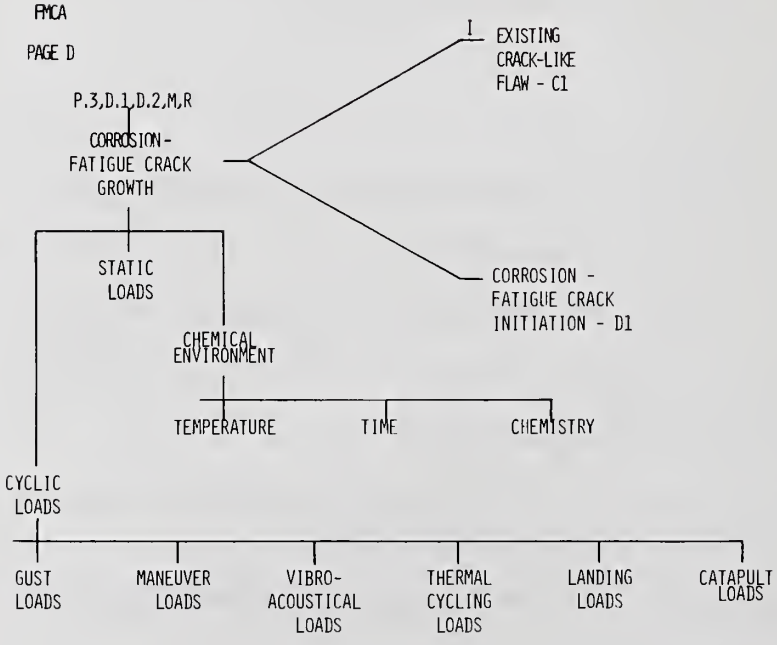


MECHANICAL SYSTEMS INTEGRITY MANAGEMENT

Robert L. Kincaid
Spectron Caribe, Inc.
Caparra Heights, Puerto Rico 00921

William S. Kincaid
Spectron Caribe, Inc.
Caparra Heights, Puerto Rico 00921

Abstract: As mechanical systems have become more sophisticated and dependence upon them more absolute, increasingly complex problems have been generated for both maintenance and management. Maintenance of these systems no longer can be treated as an isolated technical activity, but must be a vital, integral part of the entire industrial management function. Modern analytical techniques are available for determining mechanical and lubricant integrity. When this information is organized and systematized into a program for the management of maintenance, it can provide constantly updated information as to required maintenance action as well as benchmarks against which to measure the effectiveness of maintenance operations, establish trends and evaluations for projections to the future, and provide an almost unlimited source of management information as related to the mechanical systems monitored.

Key words: Atomic emission spectroscopy; cost-effective; data processing; infrared spectrophotometry; integrated reporting system; maintenance management; mechanical and lubricant integrity; MIR (multiple internal reflectance); on-condition maintenance; oscillation viscometry.

We live in an age of technology explosion. Our society is dependent upon mechanization: the mechanization of industry, transportation, construction, power generation, agriculture, natural resource extraction and processing, and national defense.

The increasing sophistication of mechanical systems has been accompanied by an increase in the complexity of problems faced in maintenance management. Each piece of equipment today represents a greater part of total productive capacity than ever before. As a consequence, repair and

down-time costs have soared. These costs are further magnified by the shortage of adequately trained mechanics and technicians, the time and distance involved in obtaining repair parts, and in many cases the problem of securing foreign exchange for purchase of parts and service.

Industry can no longer afford outdated maintenance programs. Today's problems are forcing the management of maintenance into its proper perspective. Maintenance cannot be treated as an isolated technical activity, but must become a vital, integral part of the entire industrial management function.

The responsibility of management is to promote the greatest efficiency of operations possible, and a maintenance program must therefore be judged according to the following criteria:

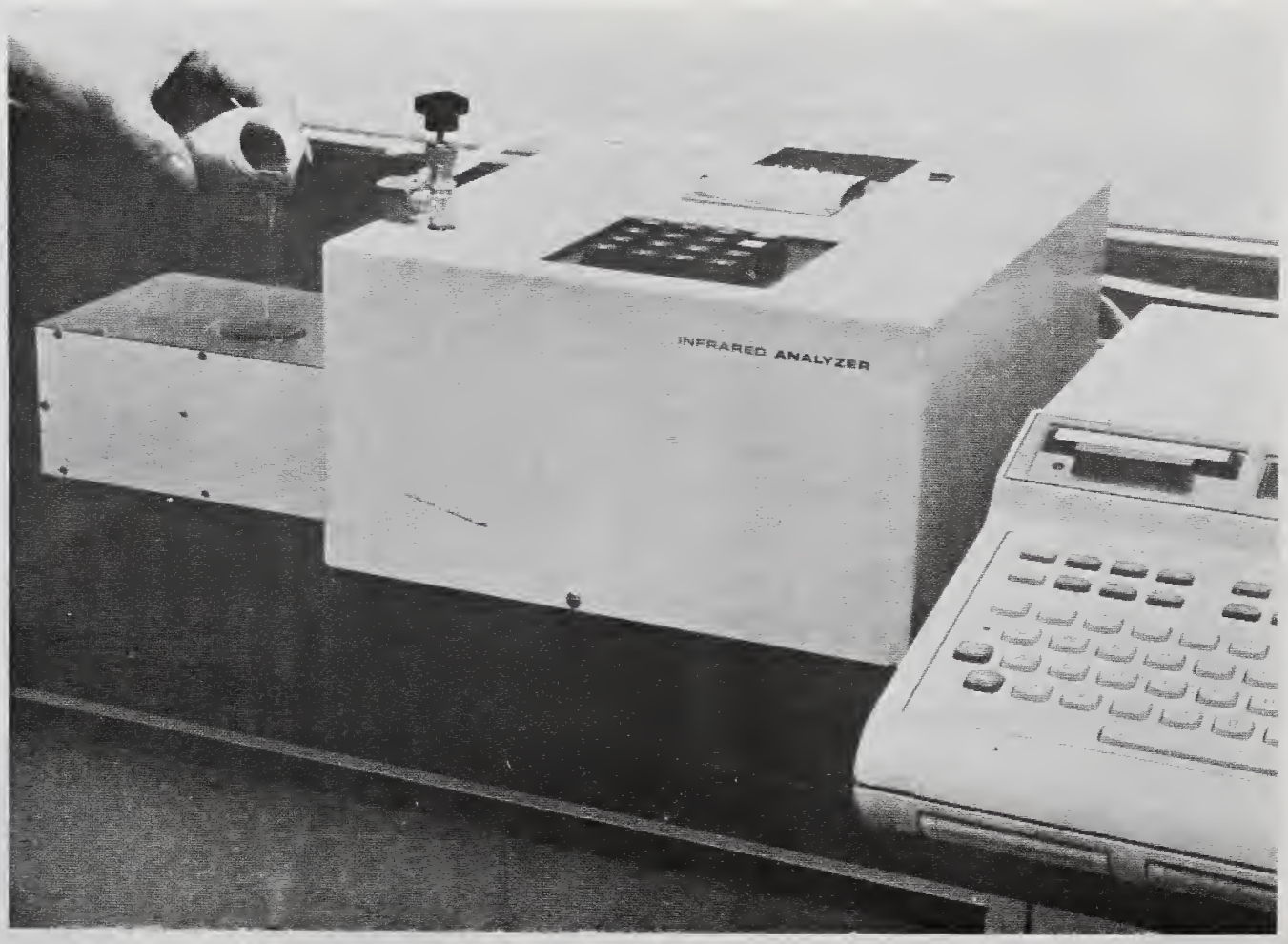
> For maintenance efficiency, it must reduce breakdowns and unnecessary repairs.
>
> For operations efficiency, it must improve the availability and reliability of production equipment.
>
> For fiscal efficiency, it must reduce expenditures and provide cost effectiveness.

As a discipline, maintenance management has lagged far behind the pace of modern industrial technology, and a major reason for this has been the lack of timely and appropriate information with which to manage. When exact knowledge of mechanical condition is available, neither time, money nor effort need be expended in unnecessary maintenance activity, and these assets can be concentrated exclusively where the need exists. This is the fundamental concept of on-condition maintenance.

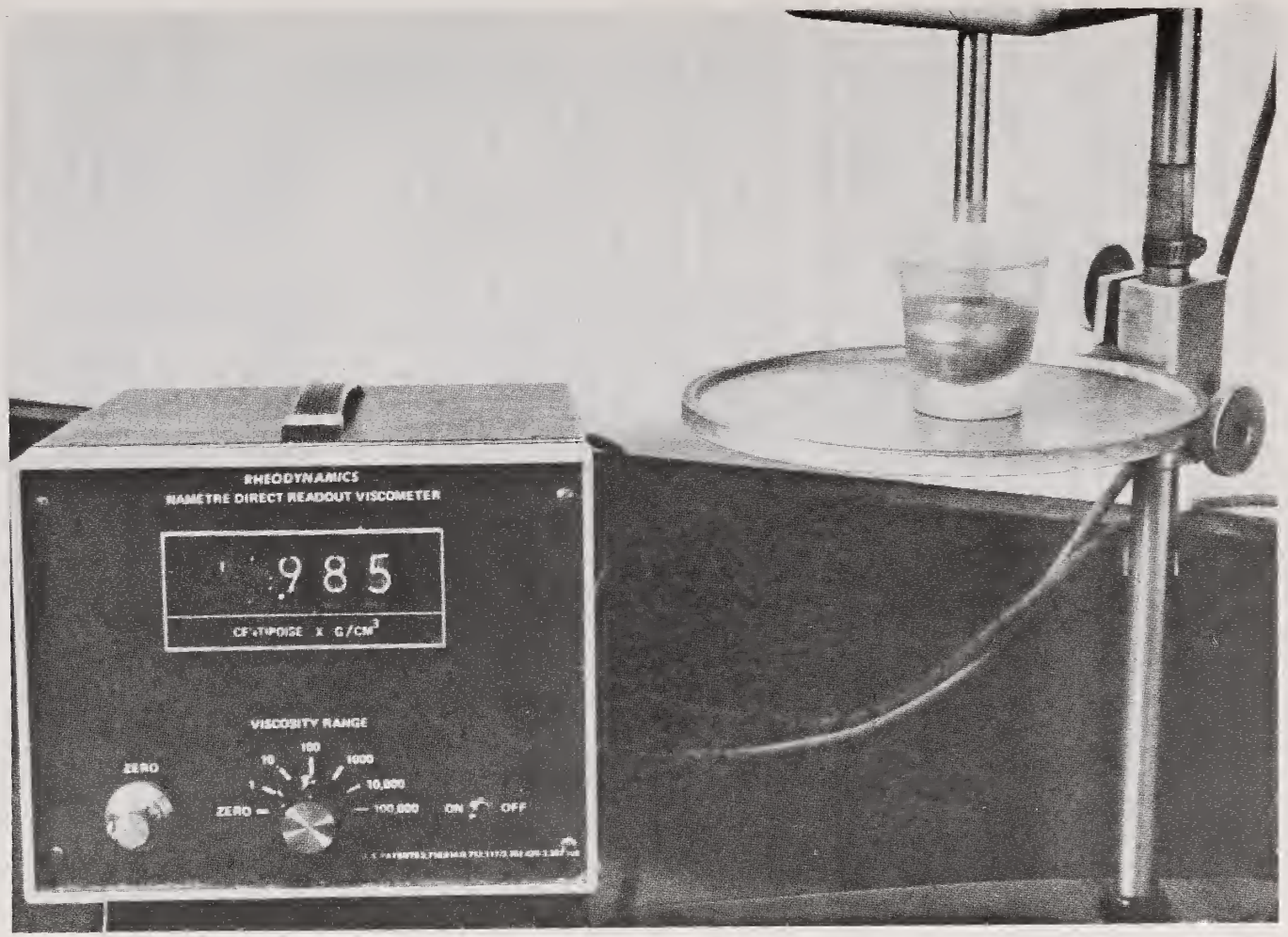
Since 1961, the efforts of SPECTRON CARIBE, INC. have focused on the development of programs to bridge the gap between current technology and maintenance management. We refer to these programs as Mechanical Systems Integrity Management. They are based on continuous monitoring of equipment condition and generate the information needed for effective on-condition maintenance.

The mechanical integrity of a lubricated system is both reflected in and influenced by its lubricant. Monitoring a lubricant can therefore reveal a system's condition. Spectron has applied advanced analytical techniques to accomplish this.

A Baird Corporation model FAS II atomic emission spectrometer interfaced to a Hewlett-Packard 9825 minicomputer. The H-P 9825 is used here as a data logger, recording analytical results on tape cartridges. These are in turn played through a central processing unit which updates the appropriate equipment files on a client's floppy disc.



A Wilks Model 80 Infrared spectrophotometer with MIR (multiple internal reflectance) sensing head. An H-P 9825 is interfaced to the instrument for use as a data logger and program controller. Oil samples are poured on the MIR for analysis, thereby eliminating the need for special sample preparation.



A Nametre Oscillation Viscometer

No sample preparation is required. The viscosity reading, sample temperature, and lubricant's parameters are used by a computer program to compute the equivalent centistokes at 40°C and 210°F.

A system's moving components are comprised of different metals and alloys, which are deposited as submicroscopic wear particles in the oil circulating around them. Abnormal wear conditions result in abnormal concentrations of these metals, which, through atomic emission spectroscopy, can be detected and measured far enough in advance of component failure that corrective action can be taken.

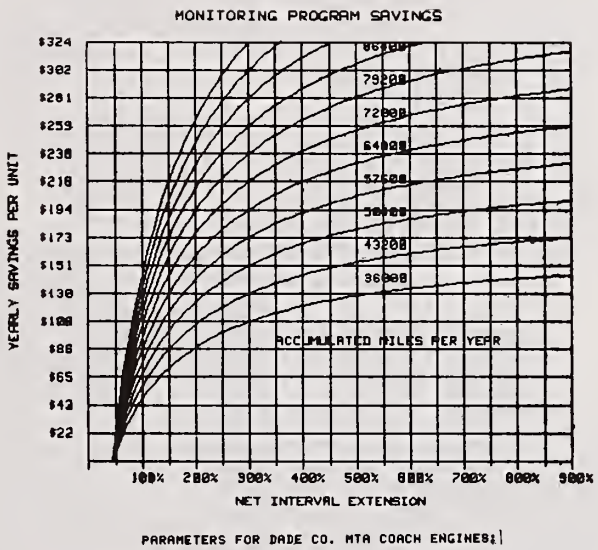
Infrared spectrophotometry, another modern and highly effective analytical technique, determines the chemical composition and contamination level of a used oil by direct comparison with the new oil. This qualitative/quantitative analysis of the differences allows a lubricant to remain in use until it is no longer in "like-new" condition.

Common problems revealed by these analyses are: contamination of lubricants with dirt, fuel, water, and entrained gases; degradation through nitration, additive depletion, and oxidation-polymerization; and abnormal equipment wear.

Conventional maintenance scheduling is based strictly on accumulated operating time. As manufacturers have no control over the conditions to which their equipment is subjected, their service interval recommendations tend to be very conservative. This unavoidably results in over-maintenance. In contrast, a monitoring program is able to distinguish between equipment which genuinely requires attention and that which does not, and allows equipment and lubricants to safely remain in operation until a need for service is identified. The potential savings resulting from on-condition maintenance are enormous. The average extension of useful lubricant life is generally sufficient in itself to make a complete monitoring program cost-effective.

The full benefit of a monitoring program can only be realized when the information it generates is properly organized and applied. Spectron offers an integrated reporting system which provides a client information at three levels: individual unit reports communicate problems and corrective action to shop personnel; sample batch reports summarize results for maintenance supervisors and focus administrative attention; monthly reports evaluate aggregate equipment condition and trends for management.

Individual unit reports combine analytical results and history to indicate mechanical conditions. Specific maintenance recommendations are furnished where problems are detected, and the equipment is classified as being either



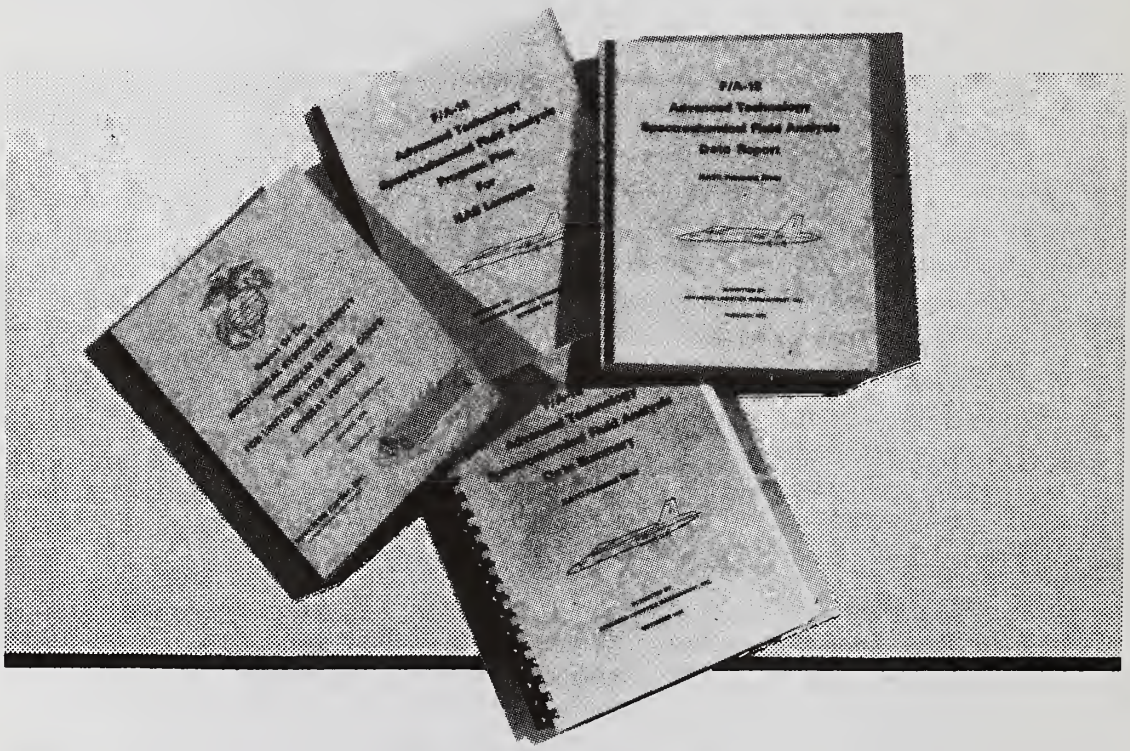
This plot projects the annual savings possible through extension of service intervals. In the case shown, it can be seen that an extension of only 40% makes the program cost-effective. Projected yearly savings are displayed on these curves as a function of net service interval extension. Each curve represents the savings associated with a particular rate of equipment usage.

critical (in need of immediate attention), borderline (highlighted for closer scrutiny or minor corrective action), or normal.

Batch reports summarize the results of each batch of samples. As well, they provide the maintenance manager with an update of equipment status, required maintenance action, and equipment due for sampling.

Monthly evaluations provide a management-oriented overview of equipment condition and program control, emphasizing trends and identifying problem areas.

The information generated by Mechanical Systems Integrity Management can serve as a basis for a wide variety of special studies as well, such as comparative evaluations of equipment, lubricants, components, and maintenance and operational procedures.

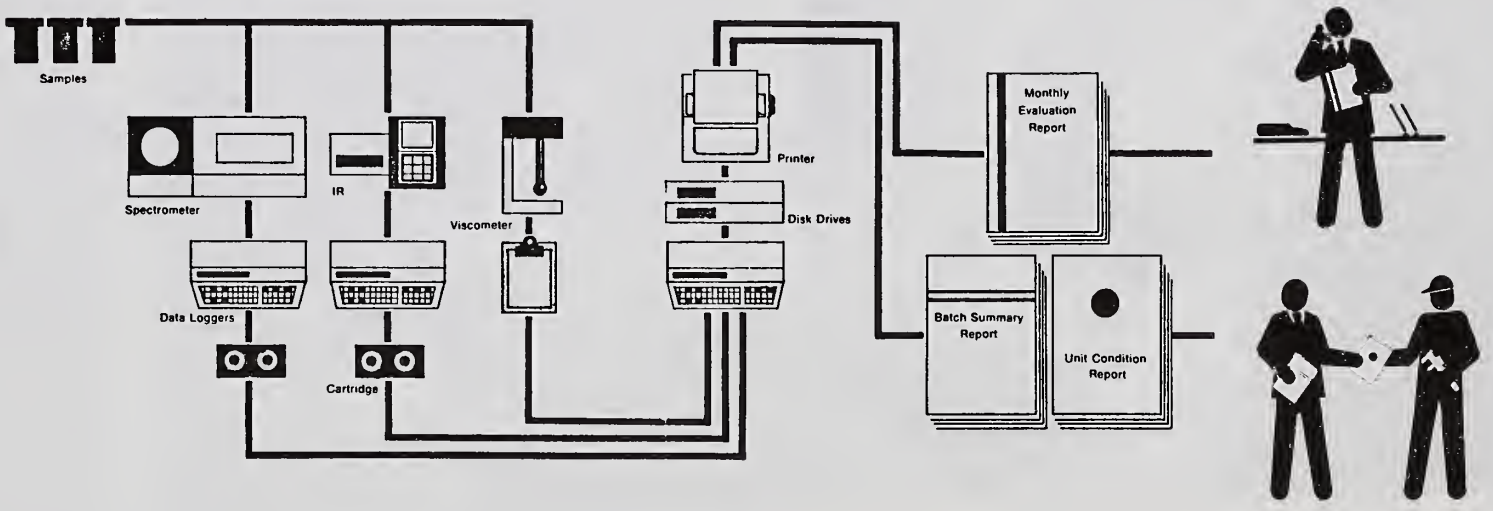


The storage of all data on discs makes it available for special studies, comparisons and statistics.

The central processing unit is composed of a Hewlett-Packard 9825 minicomputer with perpheral disc drives and printer. All reports are generated by this unit with the exception of the graphics in the Monthly Evaluation Report which are generated by a Hewlett-Packard 9845

Modern analytical tools and data processing can provide the information vital to successful maintenance management. By monitoring equipment condition, problems are detected before they develop, and the role of maintenance becomes preventive rather than remedial. Disassembly repairs shrink to a small fraction of total maintenance effort, being replaced by minor action to correct abnormalities before they can cause mechanical damage. To put this in perspective, Spectron's experience is that while as many as 20% of all samples analyzed reveal abnormalities requiring minor corrective action, less than 1% of all monitored components require disassembly inspections and repair. On-condition maintenance, through Mechanical Systems Integrity Management, makes the best possible use of available resources.

And thus, the modern technology explosion comes full-circle. It has created new and sophisticated problems for industrial management, and yet has also provided the means not only of resolving those very problems, but of establishing a sound basis for technology management.



As samples are analyzed, data is recorded on tape cartridges, which are later read by a central processing unit. The data is then filed in equipment files contained on a client's disc. The computer interprets and evaluates this data to produce individual Unit Condition Reports, Batch Reports, and Monthly Evaluation Reports.

FIELD MONITORING OF NC-MACHINES - A SYSTEM APPROACH

K-E Johansson
Linköping Institute of Technology
IKP, S-581 83 Linköping, Sweden

Abstract: In Sweden unmanned factories have become a reality. Condition monitoring (CM) of NC-machines becomes a vital concern in this type of factory and it is important that the monitoring system be integrated into the normal maintenance system of a factory. This paper addresses the following points:

- Which machine components need CM
- Which system should be used for CM
- Design of alarm systems both for a single machine and for an entire factory

The investigations which have been carried out show that each machine is unique with regard to its specific alarm limits, set-points, etc. The measurements used in condition monitoring are not necessarily absolute since interest is focused on the changes that occur over a life span. When monitoring an entire factory one should avoid building the system around one centralized master computer since each machine must be accessible to separate monitoring independent of a central computer.

Key words: Administrative system for maintenance; automatic condition monitoring; condition monitoring module; microcomputer.

GENERAL ABOUT THE MAINTENANCE FUNCTION

How Maintenance Work is Done Today in the Mechanical Industry

In most mechanical industries the major emphasis has been on corrective maintenance rather than preventive maintenance. It is only during the last three or four years that preventive maintenance has noticeably increased.

Data processing systems, which are used by many companies, are only used for following the costs of the maintenance department. In Sweden the cost for industrial equipment maintenance is about 50% of the yearly new investment volume.

Administrative systems for maintenance with rond lists and different follow-up systems are increasing in use. There is no special way to organize the maintenance department which is found to be the best solution. Both centralized and decentralized maintenance and a mixture of both are used with varying degrees of success.

Different Faults and Their Distribution

The predominant failure mode is wear, but there can be many other reasons such as: operator mistake, wrong voltage from the line, etc. One can classify the faults into different groups along with the repair time and time for trouble shooting (table 1).

Table 1

	Type of system	Trouble shooting time	Repair time
El. faults	Electronic	90%	10%
	Electrical	60%	40%
Mech. faults	Hydraulic	20%	80%
	Mechanical	10%	90%

From table 1, it can be seen that mechanical faults take much more time to repair, but are easier to locate than the electrical faults.

A typical machine in the mechanical industry is an NC-Lathe and if we are looking at the frequency distribution of the length of the failure we will have the following figure.

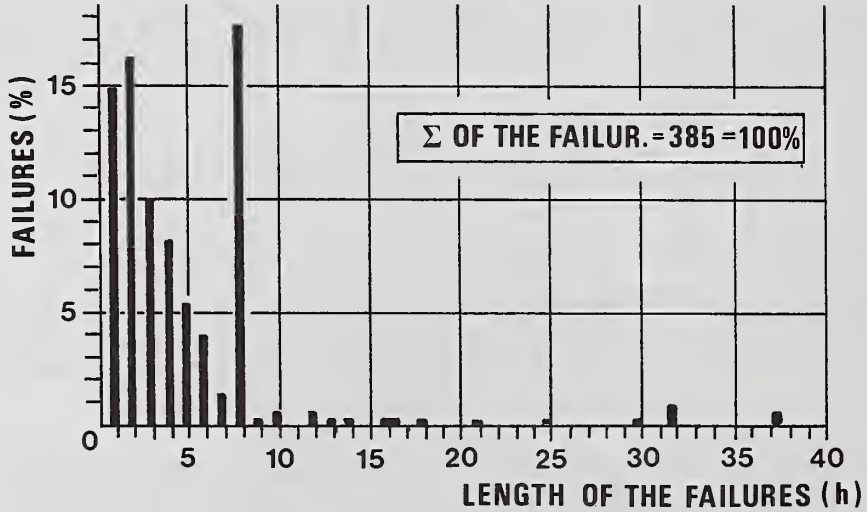


Fig. 1. Frequency distribution of the length of failures for a NC-Lathe

The total time for repair is almost the same for mechanical and electrical faults, but electrical faults predominate.

In fig. 1, almost all faults with a length of more than 5 hours are mechanical faults.

Administrative System for Maintenance

In many plants administrative systems are used to get a better follow-up of maintenance costs. If the maintenance people need to have a better follow-up system they must have their own "maintenance computer." It is true that the cost is a very important parameter, but there are many other important parameters such as MTTR (Mean Time To Repair) and MTBF (Mean Time Between Failure).

When the company is going to buy new equipment it is of great importance for the maintenance people to be able to influence the selection. This influence can easily be applied if they have the right statistics from the administrative system.

REQUIREMENT SPECIFICATION FOR CM OF A NC-MACHINE

The following demands should be met by a system which performs CM of a NC-machine:

The CM-system should be based on a real time method.

The system must have high reliability.

The system must be able to give early warning of incipient failure, thus permitting service action to be taken when no production is planned.

When a breakdown has occurred, the system should be able to rapidly identify and locate the failure.

The alarms must be graded into different levels depending on the nature of the breakdown. When an alarm is urgent the machine must be stopped by the system.

The alarms should be easily recognized by the operator as well as by the maintenance personnel.

The CM-system should be set up in such a manner that it is possible to connect it to a master-computer.

In addition to the above points which apply to a single machine the following additional demands in CM of a group of machines must be met:

Alarms should be displayed at the machine as well as at a central maintenance department.

Every separate CM-system monitoring a particular machine must function independently of the others.

The central system for collecting data should not influence the separate CM-systems.

The error messages which are obtained must be stored in the system so that a malfunction can be corrected when maintenance personnel are available.

GENERAL DESCRIPTION OF THE MAINTENANCE SYSTEM WHERE A MICROCOMPUTER IS USED

The total maintenance system consists of two parts:

a) Automatic Condition Monitoring System (ACMS)

b) Administrative system.

Most of the work in this project has been part a), but later on, part b) will be more thoroughly analyzed. The maintenance department is often one of many sub-departments in the total organization with communications in all directions. In order to build up an effective maintenance system one must put the maintenance department in the center and build the system up from this point.

Reasons to Introduce ACMS

a) Reduce downtime for the machines.

b) New machines are getting more complex; therefore they must have better monitoring.

c) Production will be unmanned, especially in the night; therefore there is a need for better condition monitoring.

d) With an effective ACMS the maintenance work will be more preventive than corrective - this means a more continuous working load.

e) To influence the machine manufacturers to design their machines for proper accesss for the installation of suitable transducers.

f) Give better data to the production-planning department.

g) The total machine service life will increase.

How to Build up an ACMS?

To be able to handle all problems in this area it was necessary to divide the system into different levels as shown in figure 2. With an ACMS one can stop at level 1 and 2 if one only wants to monitor a single machine. The systems which are used today are using only one computer to monitor all the machines; this means that level 2 is missing in these systems.

Level 2 is very important because:

a) If the maintenance computer has a failure, all machines are unattended if their computer has the direct monitoring of the machines.

b) If only one machine is monitored with ACMS, it would be too expensive to use a maintenance computer as shown in figure 3.

A condition Monitoring Module (CM-module) for a NC-Lathe is shown in figure 4.

The following measurements may be of interest:

a) By measuring the current to the feed driver the following can be noticed:
   1) Lubrication is finished.
   2) The slide goes too slow, possibly because a chip maybe between the slide and the sliding plane.
   3) The condition of the motor.

b) Main voltage - this is very important to know before looking for faults.

c) Numbers of movements in the Z- and X-slide. By indicating the number of movements one will have a value of the wear on the slides. (This is verified by Tekn. lic I-E Nelson, KTH, Stockholm).

How a total maintenance system can be applied in a normal industry can be seen in figure 2.

The integration between an ACMS and an administrative system for maintenance can be seen in figure 5.

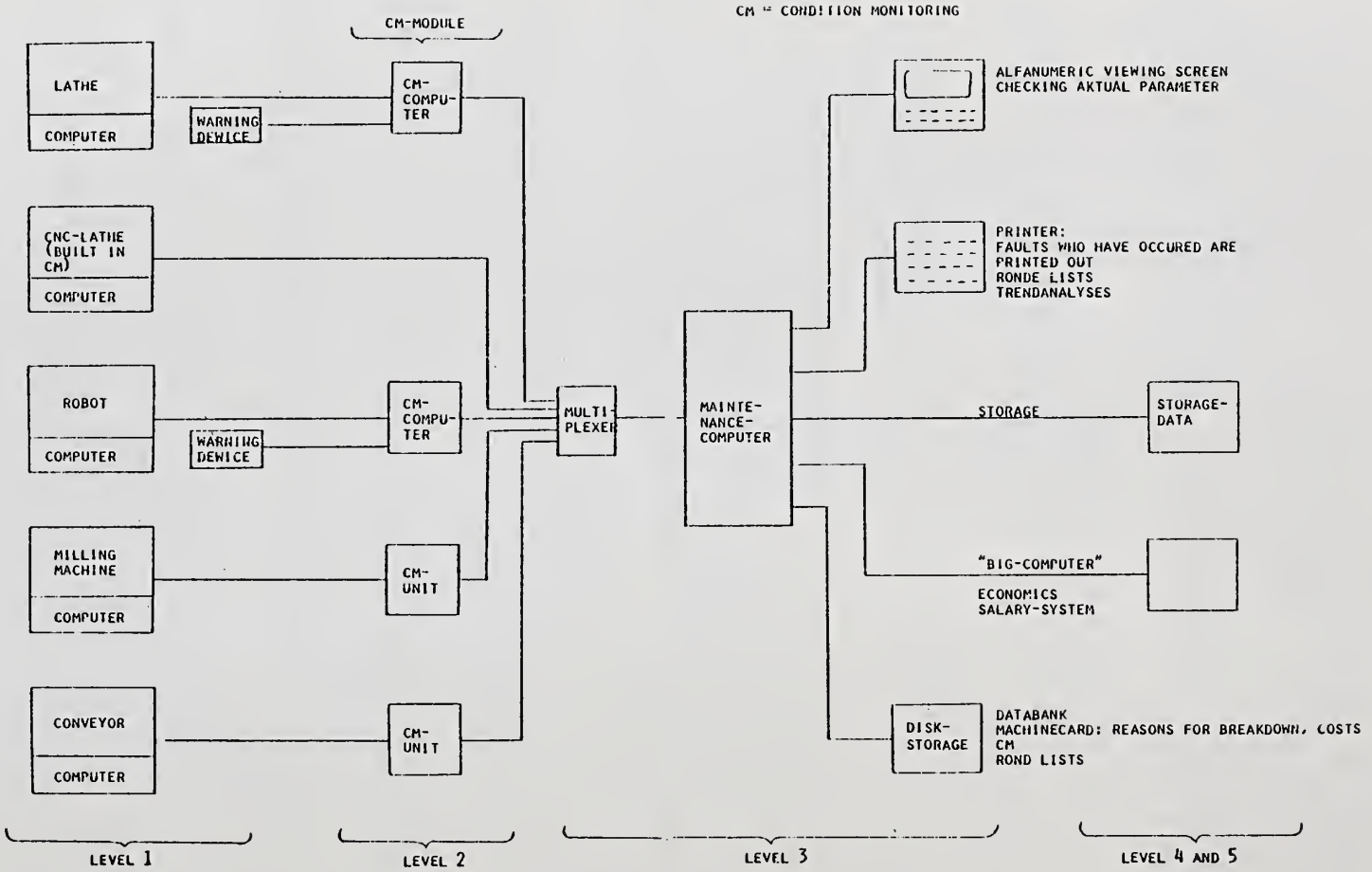


Fig. 2. Condition monitoring system for mechanical industry

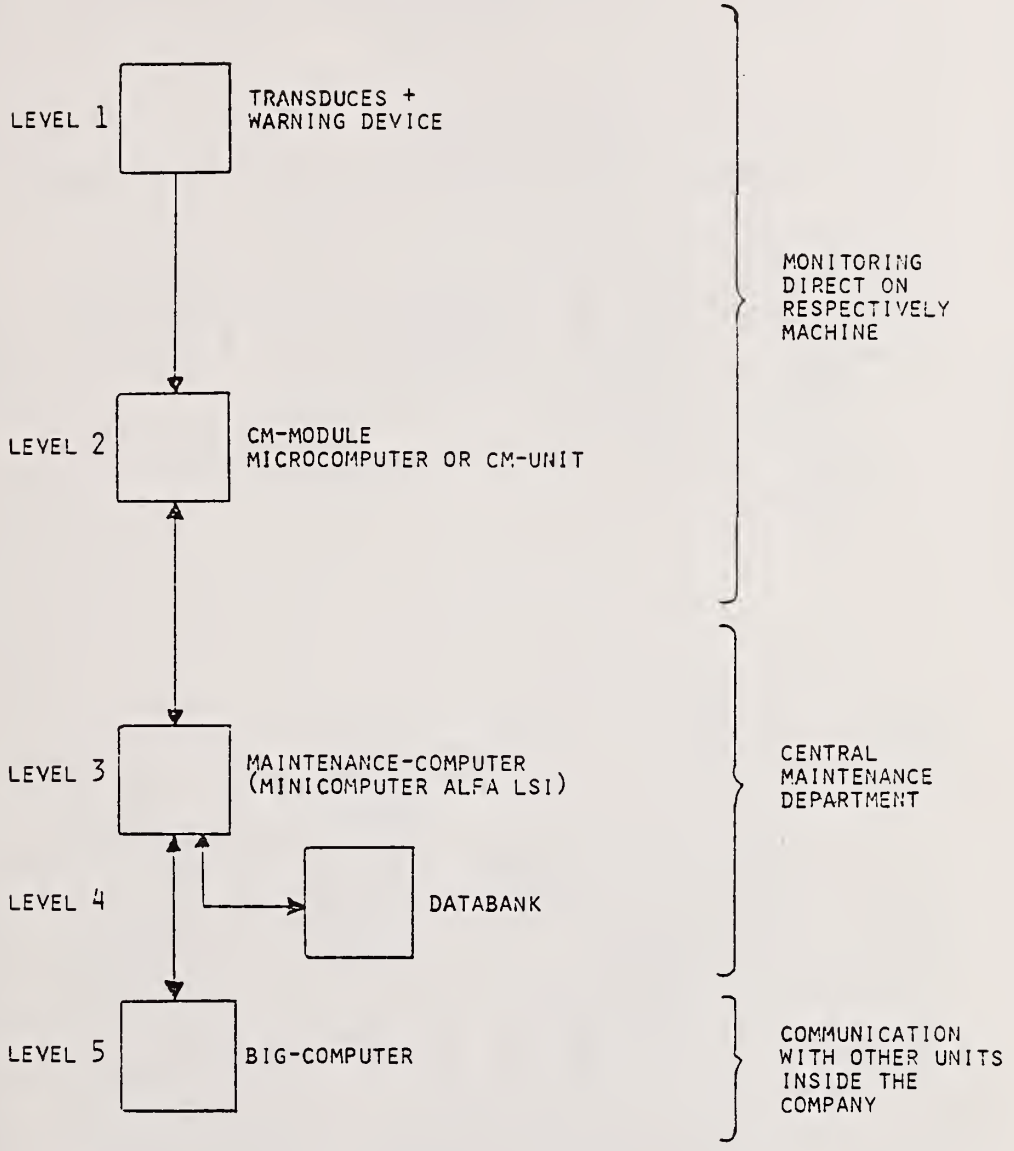
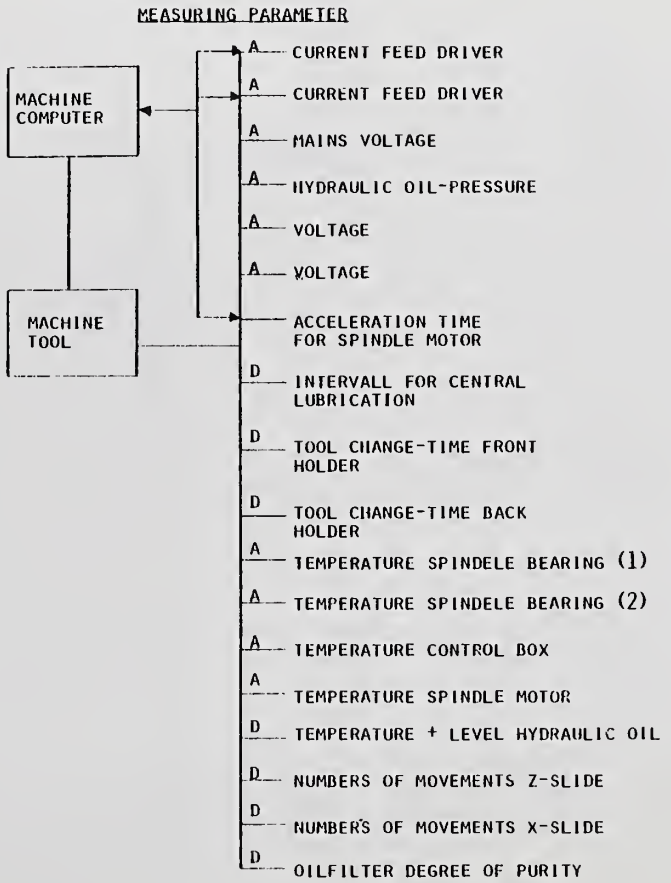


Fig. 3 Different levels in the maintenance system



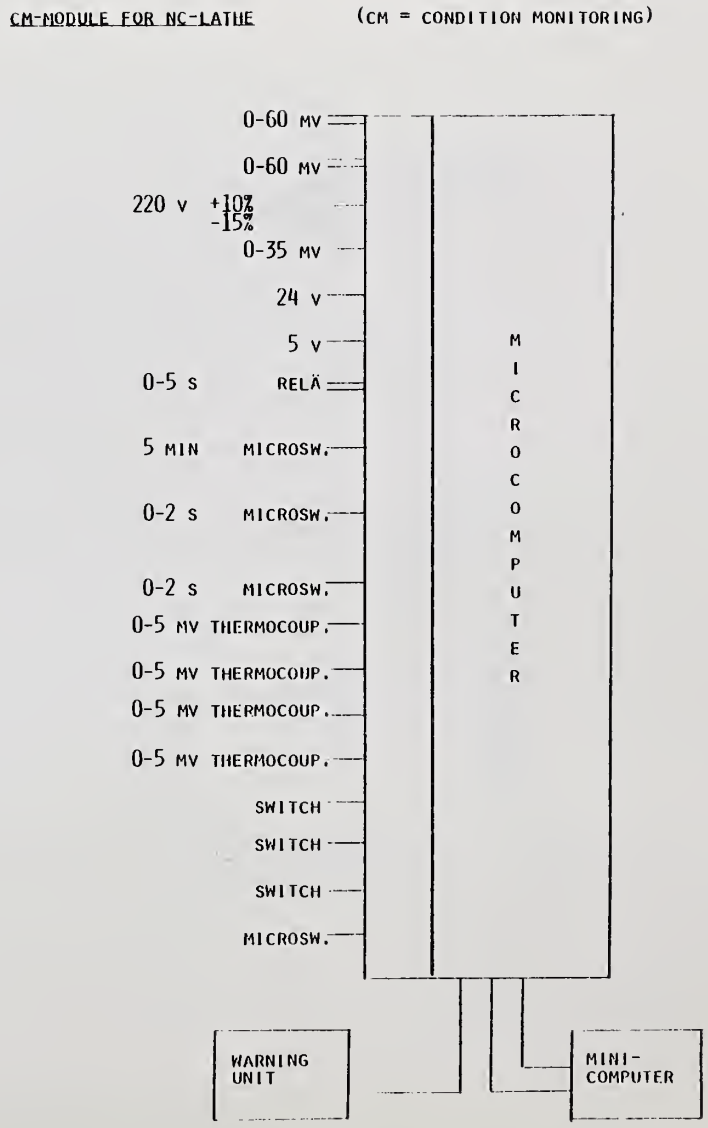


Fig. 4 CM-module for NC-lathe
(CM = Condition Monitoring)

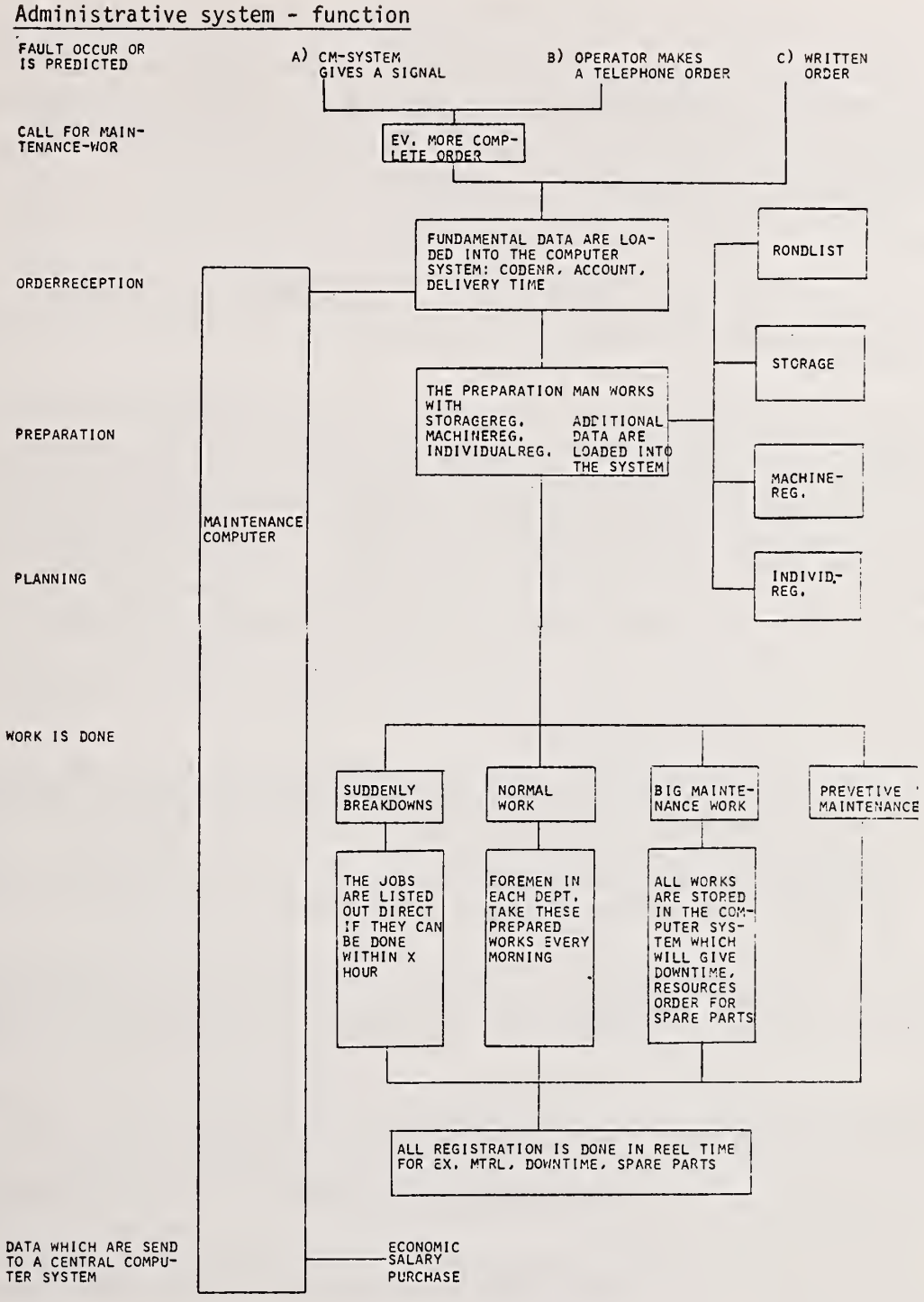


Fig. 5. Administrative maintenance system

Automatic Condition Monitoring System a Specification

The automatic condition monitoring system includes all functions from transducers located on the different machines to the data processing which is done in the maintenance computer. The different levels which will occur in the total system are shown in figures 2 and 3.

Level 1

On each machine the monitoring is done with analog and digital transducers which are placed on different parts of the machine.

A warning unit must also be placed on each machine and the warning unit must give some sort of signal when any fault occurs. This alarm signal will give information about where the fault has occurred so that the machine operator can take corrective measures. The warning unit must also be supplied with some form of equipment from which can be read the down-time and the reason for the break-down. These data will be used by both the production and the maintenance departments.

Level 2

Condition monitoring module

From figure 2 it can be seen that the CM-module can be any of three different configurations:

1. CM-computer (microcomputer).
2. CM-module is already built into the machine computer.
3. CM-unit.

The CM-module alone must do the monitoring of its respective machine even if the maintenance-computer should have a break down.

Continuous condition monitoring specifies that the following functions must be in the CM-module.

data-logging of measurement test results from different transducers, digital and analog.

comparison of actual measurement test results toward a given limit value where both an upper and a lower limit can exist.

calculation of complex values from different measurement test results, i.e., median value.

calculation of temp. derivative.

control of visual alarm when malfunction has occurred.

possibility of reading actual value for each analog signal.

possibility, from outside via maintenance-computer, to be able to control the CM-module, so that one can control a certain parameter and transform this measurement test result to the maintenance-computer for further treatment.

possibility to use AND and OR functions.

Level 3

Maintenance-computer

One function of the minicomputer which is placed in the maintenance department is to work as a data-concentrator in the automatic condition-monitoring system so that the maintenance staff has the different machines under control at all times.

When there is an alarm that some fault has occurred on a machine, this will be recorded both on a typewriter and on a viewing screen, both of which are connected to the minicomputer.

The alarm which is received from the minicomputer normally includes enough information so that there is no need for more trouble shooting - preparation of the repair work can start immediately. When the work is finished acknowledgement must be entered into the respective machine's alarm unit so that the downtime will be registered.

From figure 5 it can be seen how the administrative system for maintenance works - it can also be seen how the CM-system is connected at point a) and supplies data to the administrative system.

To make the preparation of maintenance work easier, the administrative system specifies that the planning personnel have access to the spare parts store, machine - and individual register, in real time. These data can be stored in different ways.

a) Centrally stored in the companies' databank.

b) Locally stored on a disc storage in the maintenance department.

The machine register means, for example, a complete machine tool; on the other hand, the individual register includes the different parts, such as, for example, an electrical motor of a certain manufacturer.

Level 4

Databank

All data which are not needed for calculations in real time are stored in a central databank. The data which are stored here are as per the following:

Machine reg.	-	data from all machines
Individual reg.	-	data from machine details
Spare part reg.	-	all spare parts are registered

Level 5

Communication with other units in the company

From the maintenance department one needs communications with other units in the company and this can be done via the company's main computer. Other units in the company sometimes need data from the maintenance department, for example:

a) Downtime - production department

b) Repair times - economics department

c) Reliability - department for buying new machines

DESCRIPTION OF THE MICROCOMPUTER USED IN CM FOR A NC-LATHE

The system is built around the microcomputer Intel 8080 and the configuration is presented in figure 6 below.

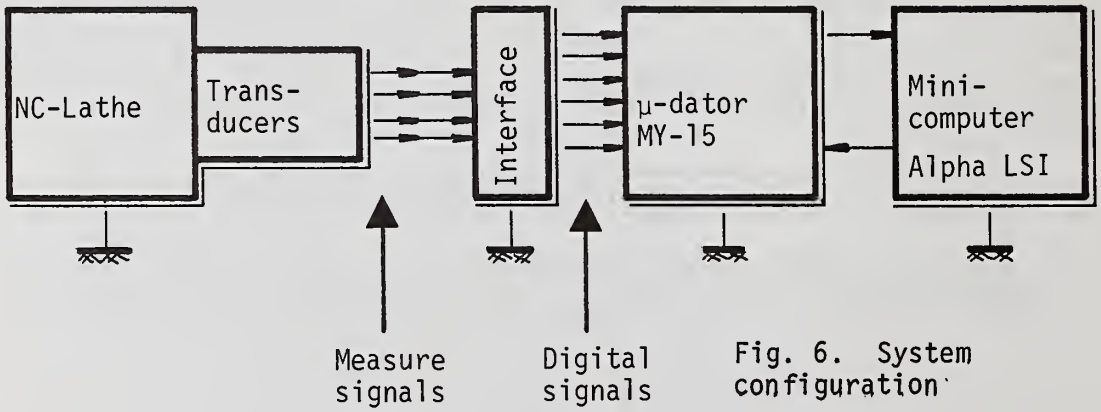


Fig. 6. System configuration

The signals from the transducers on the NC-Lathe are of two kinds:

a) analog signals

b) on/off signals

The transducer signals are often obscured by noise such as:

thyristor controllers on the NC-Lathe (high frequency).

line frequency (50 Hz).

contact-bounces.

different ground potential in the NC-Lathe's and the microcomputer's grounding system.

The analog signals are electrical voltages with differing levels from 1 mV - 30 V DC.

The computer only accepts digital signals of the type TTL in word length of eight bytes.

To be able to handle the signals in the microcomputer the signals must be transformed through the interface, and it must fulfil the following demands.

eliminate high frequency noise and noise from the line.

eliminate contact-bounces.

separate the NC-Lathe's and the microcomputer's grounding system.

give suitable signal level for transformation.

give eight bytes TTL-data out.

The interface for ANALOG signals is solved by using a differential amplifier, analog multiplexer and A/D converter as can be seen in figure 7.

The address is given from MY-15 by a plug-in-card. This card also calls and transforms data to a main computer (TTL-signals).

The interface for the ON/OFF SIGNALS is solved by using optocouplers and the interface is shown in figure 8.

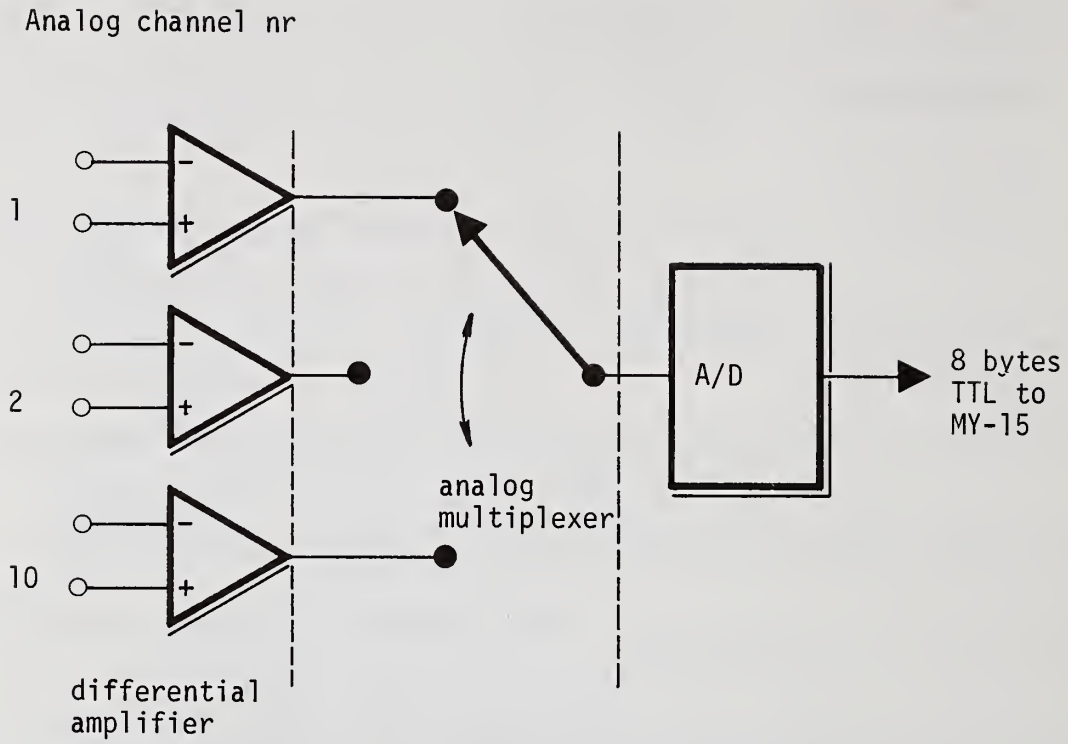


Fig. 7. Interface analog signals

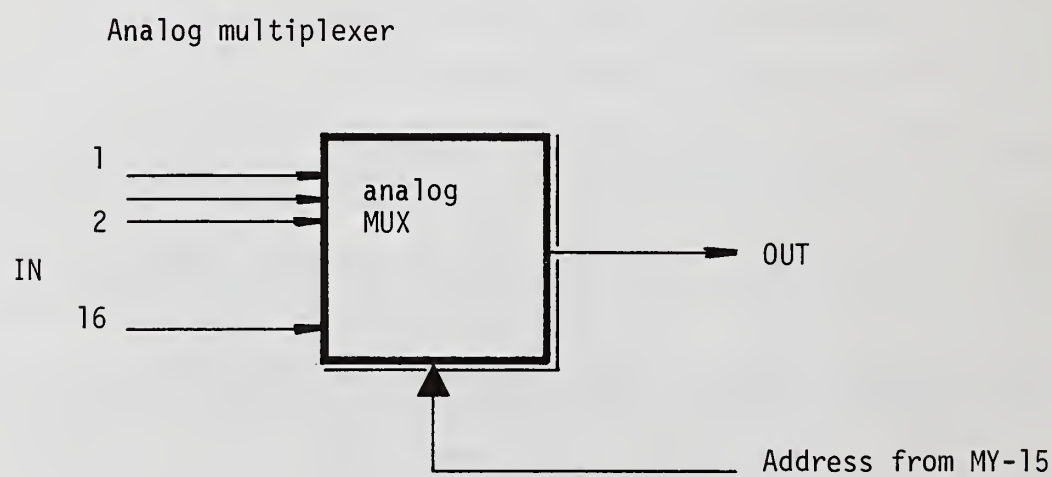


Figure 8.

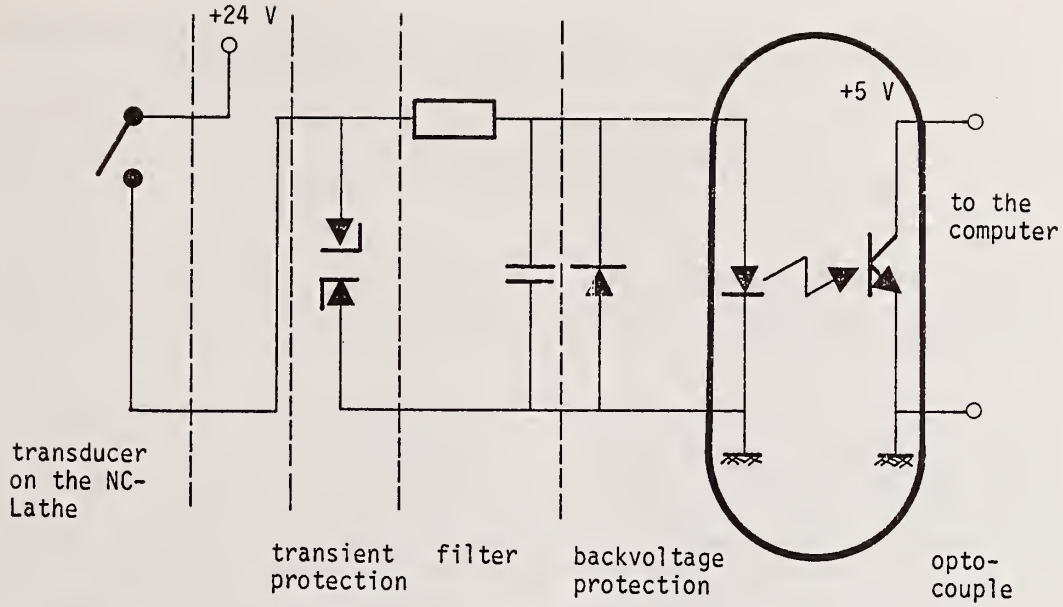


Fig. 9. Interface on/off signals

The optocoupler gives galvanic isolation between the two grounding systems (24 V resp 5V). Ground potential differences of hundreds of volts can be allowed.

The filter takes away the contact-bounces but gives at the same time a pulse with growing flank. For this reason a Schmitt trigger must be used on the 5-volt side to give the TTL-logic a strong enough pulse.

The signal levels from both analog and digital transducers vary from 2 mV - 220 V and therefore one must have special circuits to get suitable levels to the microcomputer.

The different parameters which are controlled are presented in figure 4.

Summary

By introducing an automatic condition monitoring system in the shop, the maintenance of the equipment will be much more effective and the downtime will decrease. To be prepared for unmanned production in the future it is of great importance that the monitoring of the production equipment be fully automated. Such a system is presented in this paper and it is shown how the monitoring system is integrated to an administrative system for maintenance.

A MAINTENANCE PLAN FOR A BATCH CHEMICAL PLANT

G. N. D. Seddon and A. Kelly
University of Manchester
Manchester M139PL, United Kingdom

Abstract: Many maintenance departments find themselves in one of two situations: either they are "fire-fighting", or they are over maintaining.

This paper presents a method of establishing a maintenance plan to overcome this problem. A dynamic model of the maintenance/production system is proposed as a background against which a systematic method for establishing a maintenance plan is developed. The method proposed uses a "top down" approach to analyse the maintenance requirements of a plant. Once determined, the requirements are synthesized into a maintenance plan. An example of the method as applied to a batch chemical plant is then given.

Key words: Preventive maintenance plan; maintenance effectiveness; cost effectiveness; programmed inspections.

INTRODUCTION

If a maintenance manager is to establish the best maintenance strategy for his company, he must follow the same rules as for any other industrial management problem. He needs to understand the maintenance characteristics of the plant, the relationship between maintenance and production and what the function of the maintenance department really is. In other words, he needs to be familiar with his sphere of responsibility, to accept that the maintenance production system is dynamic and to understand how such a system works. From this the maintenance objective can be defined and then, and only then, can the maintenance plan, organization and control be established. This paper is concerned with the maintenance plan. An attempt will be made to lay down a systematic method of establishing such a plan for a large continuously operating process plant.

THE PRODUCTION/MAINTENANCE SYSTEM - A DYNAMIC MODEL

In simple terms the maintenance plan is concerned with matching the best combination of maintenance procedures (Figure 1) to the particular spectrum of plant items (Figure 2). In order to do this, and also to look in detail at some of the basic ideas of maintenance management, a dynamic model of a typical maintenance-production system will be examined. The function of a plant is to manufacture a product for some given period thus providing a planned output. This output will depend upon the sales demand and its long term total can be forecast, even though there may be short term fluctuations, as with a power station for example. Thus, the long term production plan will determine the working pattern and availability requirements of the plant (e.g., 2 shifts/day, 6 days/week, 48 weeks/year at an average availability level of, say, 90%). Obviously this could change in the short term. The plant or some part of it may be in one of the following states (Figure 3):

A - in production and only running maintenance can be carried out;
B - not wanted for production (e.g., during night shift, or during feedstock shortage) and available for maintenance without production loss. This is the available-for-maintenance "window" where "stopwork" will not incur production loss;
C - taken out of production for scheduled (preventive and corrective) maintenance. Major stopwork can be carried out but there is production loss;
D - failed unexpectedly and undergoing corrective maintenance under breakdown conditions. Production is being lost and maintenance is difficult to plan;
E - failed, but due to shortage of maintenance resources, is 'waiting for maintenance'. This is the worst state of all.

The plant availability is, therefore,

$$A = \frac{T_{up}}{T_{down} + T_{up}} \quad \text{or} \quad \frac{A + B}{A + B + C + D + E} \quad \text{or} \quad \frac{\text{M.T.B.F.}}{\text{M.T.B.F.} + \text{M.T.F.M}}$$

which is one measure of the effectiveness of the maintenance department. Caution is needed when using this definition of availability since:

a) it is often difficult to cost unavailability,
b) the cause of failure may not be due to maintenance,
c) the definition assumes only two levels of performance.

THE MAINTENANCE FUNCTION AND OBJECTIVE

It can be considered that the function of maintenance (Figure 3) is to use resources (men, spares and tools) to replace, repair, adjust or modify the parts of a plant to enable it to operate at a specified availability and performance, in a specified manner over a specified time. Maintenance then affects company profitability through its influence on availability, i.e., plant output; through the cost of the maintenance resources used; and through its influence on the life of the plant. Although this is clear, it is still difficult to generalize about the maintenance objective. However, what can be stated is that the objective should be closely linked to the production plan (Figure 4). In short, the maintenance objective is to provide production with the required long and short term plant availability needed to meet the planned production at minimum cost.

THE MAINTENANCE PLAN

In simple terms the maintenance plan can be considered as being concerned with directing the maintenance resources in the best way (Figure 3) in order to achieve the planned output (1). Broadly speaking, the options are: to carry out the maintenance before plant failure (some combination of procedure 1 to 3, Figure 1); to allow the plant to fail and then carry out corrective maintenance (procedure 4); to eliminate the cause of maintenance (procedure 5). The initial choice is between procedures 1-4, whilst procedure 5 becomes important as plant operating experience is accumulated. It is becoming increasingly advantageous, because of the high cost of unavailability, to direct resources towards carrying out planned maintenance in states A, B, or C and, where possible, to use condition-based maintenance (CBM) procedures in A and/or B in order to schedule the resultant maintenance in either B and/or C. This can only be effective if there is close liaison between maintenance and production to establish the scheduling of B and the best time for C. The minor failures, not causing plant (or unit) failure (known jobs), can be handled in a similar way.

Carrying out maintenance in this fashion has a number of advantages since the maintenance resources can be planned and scheduled, a high resource utilization can be achieved; it is easier to achieve the required plant availability; the effect of unavailability can often be minimized; plant is mostly prevented from deteriorating beyond the "resource elbow" (2) which makes for better plant condition and a longer useful life. Conversely, if the strategy is to operate the plant to failure, its condition will rapidly

degenerate beyond the resource elbow (1). This will lead to a difficult planning problem, high unavailability, failures often at the worst time, poor plant condition and a short useful life. Obviously, a strategy based on some form of Planned Maintenance would appear to be essential. In practice, the difficulty is to determine the best plan for a particular plant, taking into consideration the ever-changing nature of the production situation, the consequent priorities and limitations of maintenance resources. It is worthwhile repeating that the maintenance plan must be based on the real situation and be designed to respond to the dynamics of production demand. In addition, the organization of the production and maintenance departments must be such that the importance of adhering to the maintenance plan is appreciated by both, and the communication between them must be sufficiently good to enable an effective and, where necessary, flexible maintenance schedule to be operated.

A SYSTEMATIC METHOD FOR ESTABLISHING A MAINTENANCE PLAN

It will be instructive at this point to outline a systematic method of matching maintenance procedures to plant items.

Step (i) Establishing critical plant units and maintenance windows. Determine the nature of the plant process (continuous batch, etc.). Classify the plant into units and construct a process flow diagram to include inter-stage storage. Carry out a simple 'consequences of failure' analysis. Determine the production plan and therefore its pattern of operation and expected unit availabilities. From such information determine (a) the critical plant units, perhaps even ranking them according to the cost and consequences of failure, (b) the schedule of maintenance windows for the plant and units, including consideration of the possibility of random production stops.

Step (ii) Classify the plant into its constituent items. This will be a complete classification in the case of critical units, and a partial classification in the case of non-critical units.

Step (iii) Determine and rank the effective procedures. Establish the effective procedures for each item and determine the best of these from cost and safety factors. In general the procedures for the simple items will be reasonably certain and mostly running maintenance. However, this will not necessarily be so in the case of the complex items and the best approach is often to identify if possible a simple method of condition checking. Such a procedure should establish the following:

Item	Bearing
Timing	C.B.M. Shock Pulse Check
R or S	R
Periodicity	M
Time and labour	15 min. 1 fitter
Initial maintenance action	Replace bearing
R or S	S
Periodicity	Approx. 2 years
Time and labour	3 hrs. 1 fitter
Secondary action	None

Step (iv) Establish a schedule for the identified stopwork. This schedule will obviously depend on whether the plant is a series continuous, parallel batch, or a fleet system. Fleet or parallel systems differ from series continuous ones in that the units are independent of each other and a degree of spare capacity is usual. Consequently, the maintenance is usually all stopwork and scheduled at unit level, without production loss, into daily, weekly, monthly, etc., inspection and service schedules. Since the series continuous plant is the most difficult to schedule, it will be considered in more detail.

Rank the stopwork in order of increasing periodicity; for the same periodicity rank in order of decreasing repair time, e.g.

ITEM	ACTION	EXPECTED PERIODICITY	STOP TIME	BEST PROCEDURE
A	Replace	M	5 hr	Visual Inspection
B	Replace	M	2 hr	Shock pulse
C	Repair	M	1 hr	Time-based
D	Replace	2M	5 hr	Time-based
E	Replace	4M	1 hr	Shock pulse

This stopwork can now be compared with the schedule of maintenance windows. If the stopwork is less than the time available for maintenance (State B, Figure 3), then consider a plan based on this schedule. Obviously, the periodicities can be rationalized to make the best use of time and resources. If the stopwork exceeds the time available for maintenance, or indeed if there are no maintenance windows, then consider a plan based on an agreed production stoppage (State C, Figure 3), the initial periodicity of such a schedule being based on the lowest periodicity item (see above table). Where possible CBM should be used to determine the best time for such a stoppage and the extent of the subsequent opportunity maintenance. What must also be

considered is the fact that plant failures will still occur, in spite of the preventive effort. The failures will be of two types, those affecting plant output and those that might do so in the future. In the first case such plant failures can be taken advantage of via opportunity maintenance, if CBM is used to monitor the condition of critical items. In the second case, a list of "Known Jobs" should be kept and dealt with during the next convenient scheduled stop. Again, the resources necessary to carry out this work can now be organized.

Step (v) Establish a schedule for running maintenance. In this case the work is largely independent of production and can be scheduled to make the best use of resources. This will normally result in inspection and lubrication routines.

Step (vi) Corrective maintenance. Instead of the above plan, the plant could be operated to failure, in conjunction with opportunity maintenance. However, in most cases, especially if unavailability cost is high, this is a very expensive policy and can only be justified if the failures are unpredictable and their onset undetectable.

In spite of preventive maintenance there must still be some failures. These have to be planned for in terms of spares, methods, documentation and decision guidelines. Such planning should be reserved for critical plant units.

A MAINTENANCE PLAN FOR A SECTION OF A CHEMICAL PLANT

Introduction

A chemical plant producing organic chemicals is taken as an illustrative example. An outline of the plant is shown in Figure 5. The plant manufactures a wide range of similar organic chemicals. Some of the products are soluble in water and some are insoluble; the plant is divided into two sections to accommodate this. The products are made and isolated in the reaction streams, they are adjusted for quality and then dried, leaving the plant in powdered form. The insoluble products require extra processing stages (particle size reduction and clarifying) and there is a facility for packaging them as liquids. The reaction streams operate in batch mode, and one stream is not readily interchangeable with another, each being adapted to a selection of the range of products. The streams used for finishing the products are interchangeable, they operate in a semi-continuous mode. It can be appreciated that with a plant of this complexity, production scheduling can play as great a part as effective maintenance in achieving a high

utilization. In addition to the main product flows, the plant is supported by a full range of chemical and engineering services. Commonly used primary chemicals and intermediates are held in bulk and can be transferred to appropriate parts of the plant. Salt is pneumatically conveyed to the reaction streams and flake ice is transferred in a similar manner. The reaction streams are computer controlled and the rest of the plant is remotely controlled so the plant can be operated by a small staff.

This example will concentrate on a typical reaction stream as shown schematically in Figure 6. Reaction Unit 1 (RU1) is charged with one component. A second component is added and Reaction 1A takes place. The contents of RU1 are then transferred to RU2 where Reaction 1B takes place. Meanwhile, a third component has been prepared in the Preparation Unit and has then been transferred to RU3. Reaction 2 takes place when the contents of RU2 are added to RU3. RU3 now contains the product either in solution or suspension. The product is isolated and filtered through the Filter Press Units 1 and 2. The filter cake is washed and then discharged into the Disperser Unit. The disperser takes advantage of the thixotropic properties of the filter cake and beats it into a liquid with a high speed agitator. The product is discharged from the disperser into an intermediate storage tank.

The outline description of operations illustrates their sequential nature. It will be appreciated that the various stages of the reaction process take different lengths of time, and that these times vary from product to product. It will also be appreciated that various washing out procedures are required between batches. Thus, certain units can become bottleneck units during the production of particular products and non-bottleneck units are then less heavily utilized. However, because of the variability from one product to another, it is very difficult to predict whether a certain unit will be in use at a particular time, except in the very short term.

Description of Units

A brief description of the units and their major items and principal maintenance follows.

Preparation Unit

Mild steel rubber-lined vessel (1500 gal): The rubber is subject to deterioration and to damage, requiring periodic inspection and repair, with replacement after 10 years.

Agitation system: 2-speed AC motor; Worm reduction gearbox; Mild steel rubber-lined paddle agitator

Level instrumentation (dp cell): Replacement or calibration only possible when vessel empty

Temperature instrumentation: Thermocouple in tantalum clad pocket

Steam injection posts:

Pumping system (transfer and re-circulation): 2-speed AC motor; Mono pump; Pump protection instrumentation (pressure switches and logic)

Weigh vessel system: Mild steel rubber-lined vessel (300 gal); Weighing mechanism; Weigh scale instrumentation

Pipework: Mild steel rubber-lined; GRP/PVC lined; Valves and fittings

Reaction Unit 1

Mild steel glass-lined with welded jacket (1500 gal): Pressure vessel inspection necessary (jacket classed as steam receiver)

Agitation system: AC motor; Worm reduction gearbox; Agitator gland - requires periodic lubrication and adjustment; Agitator (stainless steel anchor)

Temperature dip pipe:

Weigh vessel (as for PU):

Powder hopper:

Powder feeder: Variable speed drive - hydraulic

Coolant re-circulation system: AC motor; Pump (centrifugal)

Pipework: Mild steel glass-lined, stainless steel, G.R.P.; Valves and fittings

Reaction Unit 2

As RU1

Reaction Unit 3

Mild steel rubber-lined vessel in ring sections (10,000 gal): Rubber subject to deterioration and damage

Agitation system: DC variable speed motor; Worm reduction gearbox; Mild steel rubber-lined paddle agitator

Level instrumentation (dp cell):

Temperature instrumentation: Thermocouple in tantalum clad pocket

Steam injection posts:

Weigh vessel: As for PU

Pumping system 1 (re-circulation and filter press feed): DC variable speed motor; Mono pump; Pump protection instrumentation

Pumping system 2 (filter press feed): As for pumping system 1

pH Instrumentation: pH probe

Pipework: Mild steel rubber-lined, GRP/PVC lined; Valves and fittings

Filtration Unit 1

Semi-automatic recessed plate filter press: Press closing system; Motor; Gears; Closing screw

Plate separating system: Motor; Gearbox; Mechanism

Filtrate washing system: GRP vessel (300 gal); AC motor; Centrifugal pump

Flow instrumentation:

Pressure instrumentation:

Pipework: GRP/PVC lined; Valves and fittings; Cross wash valves replaced every 3 years

Rubber belt conveyor: AC motor; Gearbox

Disperser Unit

Stainless steel vessel:

Agitation system: AC motor; Butterfly agitator - accelerated seal wear due to abrasive product

Discharge pump: AC motor; Centrifugal pump

Pipework: GRP/PVC lined; Valves and fittings

Existing maintenance policy

The existing maintenance policy is to perform essential lubrication on a running basis, and to shutdown the entire stream for approximately 5 days each year. This enables internal inspection of the vessels, replacement of certain valves on rotation, and overhaul of pumps if necessary. The shutdown is also used for rehabilitation work, and for the implementation of modification work. It may be extended to allow for the replacement of vessels or vessel sections.

Systematic Method

Step (i) The plant is operated in batch mode on a continuous basis. Because of product variations it should be assumed that the plant is "occupied" continuously, although individual units may be unoccupied at times during the operation of the plant. The plant has already been classified into units for the purposes of description. The consequences of failure of a particular item are dependent upon the stage of the process. However, since most failures are discovered when an item is required, it can be assumed that most failures will cause a delay to the process. The cost of the delay is the opportunity cost of the quantity of product that could have been made during the delay, i.e., the contribution from the sale of that quantity of product. Under these circumstances all units except the filtration units are critical since failure of one filtration unit will reduce the capacity of the stream to 50%. Moreover, there is no schedule of maintenance windows, although it may be possible to find windows of several hours duration on certain units only at short notice. This latter observation has important implications for the scheduling of non-urgent breakdown repairs and certain preventive stopwork; close co-operation between production and maintenance departments is required.

Step (ii) An example of a detailed classification is given in Figure 7.

Step (iii) A simple example of the approach to be taken is given by rolling element bearings in, say, a centrifugal pump fitted with a mechanical seal. Under certain circumstances failure of the bearings can lead to failure of the mechanical seal and even to damaging the impeller. The options are:

a) operate to failure,

b) fixed-time replacement (every 24 months),

c) condition-based replacement based on a monitoring scheme, e.g., subjective judgement (look, listen, feel), objective measurement (vibration level, shock pulse value, kurtosis value), (3-monthly inspection).

The selection of c) would be preferred, not only for preventing bearing failures, but also because it provides a useful peg on which to hang general condition or housekeeping checks. Thus, a complete instruction for the item would be

Item	Centrifugal pump
Timing	CBM : SPM/Kurtosis + visual (seal, housekeeping)
R or S	R
Periodicity	3 months
Time and labour	10 mins. 1 inspector
Initial Maintenance Action	Replace pump
R or S	S
Periodicity	Approximately 24 months
Time and labour	2 hrs. 1 fitter
Secondary action	Recondition pumps

A more complex example is given by the rubber-lined reaction vessel. The item itself is simple enough, it consists of four components; cover, top section, bottom section and base. The rubber lining on the sections and base is subject to permeation by chemicals over a period of time. The rubber can also be damaged accidentally. Once the rubber has been penetrated, rapid corrosion of the parent metal takes place. Further deterioration of the surface of the rubber could lead to particles of rubber contaminating the product. The present practice is to carry out an internal visual/tactile inspection. As a result of this inspection, rubber repairs may be necessary. The range of procedures to be considered can be summarized as:

a) operate to failure,
b) fixed-time internal inspection,

c) fixed-time external inspection (e.g., through manhole),
d) fixed-time electro-chemical measurements,
e) continuous electro-chemical monitoring,
f) product sampling for contamination (at levels below current acceptable level).

Although d) and e) are attractive CBM procedures, only lining failure in terms of penetration is detectable and no indication of the surface condition of the lining is given. f) would appear to be an appropriate CBM procedure for this failure mode. However, the deterioration of the rubber is thought to be due to the effect of specific chemicals which could bring about sudden changes in condition. Thus, the frequency of measurements would have to be high in order to give a failure prediction with an acceptable level of confidence. Procedure c) would be suitable if the surface could be assessed visually remotely, e.g., by use of closed circuit television, etc. Procedure a) is unacceptable on grounds of safety, let alone other costly consequences of failure. Therefore, until a more suitable alternative is developed, the existing procedure of fixed-time internal inspections is all that remains. Replacement of vessel sections will take place according to condition. This can be detailed as follows:

Item	Reaction vessel - rubber lining
Timing	Fixed time
R or S	S
Periodicity	12 months
Time and labour	2 fitters for 2 days - 1 inspector for half a day
Initial Maintenance Action	Repair in situ
R or S	S
Periodicity	24 months
Time and labour	48 hours elapsed time - 2 rubber men for 8 hours
Further maintenance actions	1. Remove and replace vessel section 4 fitters for 40 hours - 4 heavy gang for 16 hours 2. Strip rubber and reline sections - contractors

Step (iv) Due to the nature of the plant (i.e., parallel batch streams) the step (iv) of the general approach outlined in section 5 has to be modified.

a. List the stopwork as shown in Table 1 and separate the stopwork which can be carried out in the maintenance windows and that which requires the stream to be taken out of production.

b. Establish a schedule for carrying out the 'maintenance window stopwork'. Since this work does not require the shutting down of a stream the schedule can be for the whole of the plant. The schedule is established from Table 2 and written in the form of a Bar Chart or as schedule on a computer; the objective being to achieve a high labour utilization. In this particular case the schedule is completely condition-based and only the timing of the actions are scheduled. The resulting work is reported (the maintenance action) and carried out in the window (or some subsequent window) as corrective maintenance.

The execution of this schedule requires close liaison between production and maintenance supervisors.

c. Establish a schedule for the stopwork that requires the stream to be taken out of production (see Table 3).

The schedule can be established by ranking the stopwork by periodicity and time for each stream and proceeding as for the previous example. Since there are 6 streams the stops for each stream should be scheduled on a Bar Chart so as not to coincide and where possible to incorporate known jobs and window maintenance. The main aid in this case is to minimize the cost of production loss.

In this example it was found that although the inspection of the rubber lining of the vessel necessitated a scheduled production stop, very few of the other preventive maintenance activities actually lined up with this new window. Thus, the successful implementation of the programme would rely on close communication between the maintenance and production departments in order to carry out preventive maintenance activities during windows in production. This implies that much of the stopwork can be scheduled only in the short term.

The importance of Step (iii) cannot be emphasized too strongly. If, for example, a more remote type of vessel inspection were possible, the whole of the stopwork programme could be re-organized. Obviously, this is the long-term plan for the plant which can be modified in the light of unexpected failures or production stoppages. It will be appreciated that the success of the stopwork schedule and, therefore, of the plan, relies heavily upon condition monitoring.

Step (v) From the above schedule the running maintenance can be extracted, added to the remaining running maintenance (e.g., lubrication), divided into trades and scheduled into

routines and services. Such work is independent of the state of the plant.

Step (vi) From the point of view of corrective maintenance, it is important to identify those items that in spite of monitoring might still fail unexpectedly, and cause serious disruption to production.

SUMMARY

Firstly, it is important to point out that the example was considerably simplified to illustrate a number of important principles. However, this accepted, the question that must now be answered is whether the alternative plan is an improvement over the existing plan - in other words, is it cheaper in terms of the combined effort of unavailability and the cost of resources. Although it is difficult to quantify the improvement, it will be obvious that some improvement should indeed result. The difficulty comes from the uncertainty in forecasting the level of emergency maintenance that will result from the new plan. However, since the plan is based on CBM methods, even if more emergency work than that forecast occurs, it should be easier to minimize its effect on the production output. The authors cannot emphasize enough the considerable advantage for the planning of maintenance work that stems from knowledge about the condition of plant. It is hoped that the new plan will result in a movement from situation (a) in Figure 8 to situation (b).

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No.	Item	Description of Work	Frequency	Time and Labour	Items in Stream	Items in Plant	Comments
1	Pump	Inspect and test	2 M	30 Mins 1 Insp	6	36	Maintenance Window - Scheduled
		Renew seal	6 M	30 Mins 1 Fitter			Maintenance Window - On Inspection
		Replace pump	1 Yr	1 Hr 1 Fitter			Maintenance Window - On Inspection
2	Filter press	Inspect and test	3 M	30 Mins 1 Insp	2	12	Maintenance Window - Scheduled
		Adjust press mechanism	6 M	30 Mins 1 Fitter			Maintenance Window - On Inspection
		Adjust press controls	6 M	30 Mins 1 Inst			Maintenance Window - On Inspection
		Replace motor	2 Yr	1 Hr 1 Fitter 1 Elect			Maintenance Window - On Inspection
3	Vessel (rubber lined)	Inspect rubber	1 Yr	2.5 Days 2 Fitters 1 Insp	2	20	Stream Shutdown - Scheduled
		Repair rubber	2 Yr	2 Days 2 Rub rep			Stream Shutdown - extra work
4	Vessel (glass lined)	Pressure vessel inspection	2 Yr	2.5 Days 2 Fitters 1 Insp	2	4	Stream Shutdown
5	Valve Type A	Replace	2 Yr	1 Hr 1 Fitter 1 Inst	20	120	Stream Shutdown
6	Disperser	Replace bearings	2 Yr	8 Hrs 2 Fitters	1	6	Maintenance Window + - On SPM
7	Valve Type B	Replace	5 Yr	1 Hr 1 Fitter 1 Inst	30	180	Stream shutdown

TABLE 1 - LIST OF STOPWORK

ITEM	TIMING	R/S	FREQUENCY	TIME AND LABOUR	INITIAL ACTION	FREQUENCY	TIME AND LABOUR	SECONDARY ACTIONS
Pump	Inspection	S	2 months	30 mins 1 inspector	a) replace seal	6 months	30 mins 1 fitter	Recondition seal
					b) replace pump	1 year	1 hour 1 fitter	Overhaul pump
Disperser	SPM Bearings	R	2 months	10 mins 1 inspector	replace bearings	2 years	8 hours 2 fitters	
Filter Press	Inspection	S	3 months	30 mins 1 inspector	a) adjust press mechanism	6 months	30 mins 1 fitter	
					b) adjust press controls	6 months	30 mins 1 instrument technician	
					c) replace motor	2 years	1 hour 1 fitter 1 electrician	Overhaul motor

TABLE 2 - MAINTENANCE WINDOW PLAN

ITEM	TIMING	FREQUENCY	TIME AND LABOUR	INITIAL ACTION	SUBSEQUENT ACTION
Reaction Unit 3	Scheduled rubber inspection	1 year	2 fitters 1 inspector 2.5 days	a) repair rubber b) replace vessel	
Reaction Unit 1 & 2	Schedule PV inspection	2 years	4 fitters 1 inspector 2.5 days	replace glass lining	
Valves Group A	Scheduled replacement	2 years	2 fitters 1 inspector 2.5 days	replace	overhaul
Valves Group B	Scheduled replacement	5 years	2 fitters 1 instrument technician 4 days	replace	overhaul

TABLE 3 - SCHEDULED SHUTDOWN PLAN

	TIMING (WHEN)	ACTION (WHAT)
A	OPERATE TO FAILURE	Replace or Repair after Failure
B	FIXED TIME MAINTENANCE	Adjust or Repair or Replace at fixed periods
C	FIXED TIME INSPECTION	Inspect via equal or variable inspection periods then Adjust / Repair / Replace on CONDITION
D	CONTINUOUS INSPECTION	Inspect on continuous basis — then Adjust / Repair / Replace on CONDITION
E	OPPORTUNITY MAINTENANCE	Inspect item at time, based on some other item's maintenance / inspection period.

FIGURE I. ALTERNATIVE MAINTENANCE PROCEDURES.

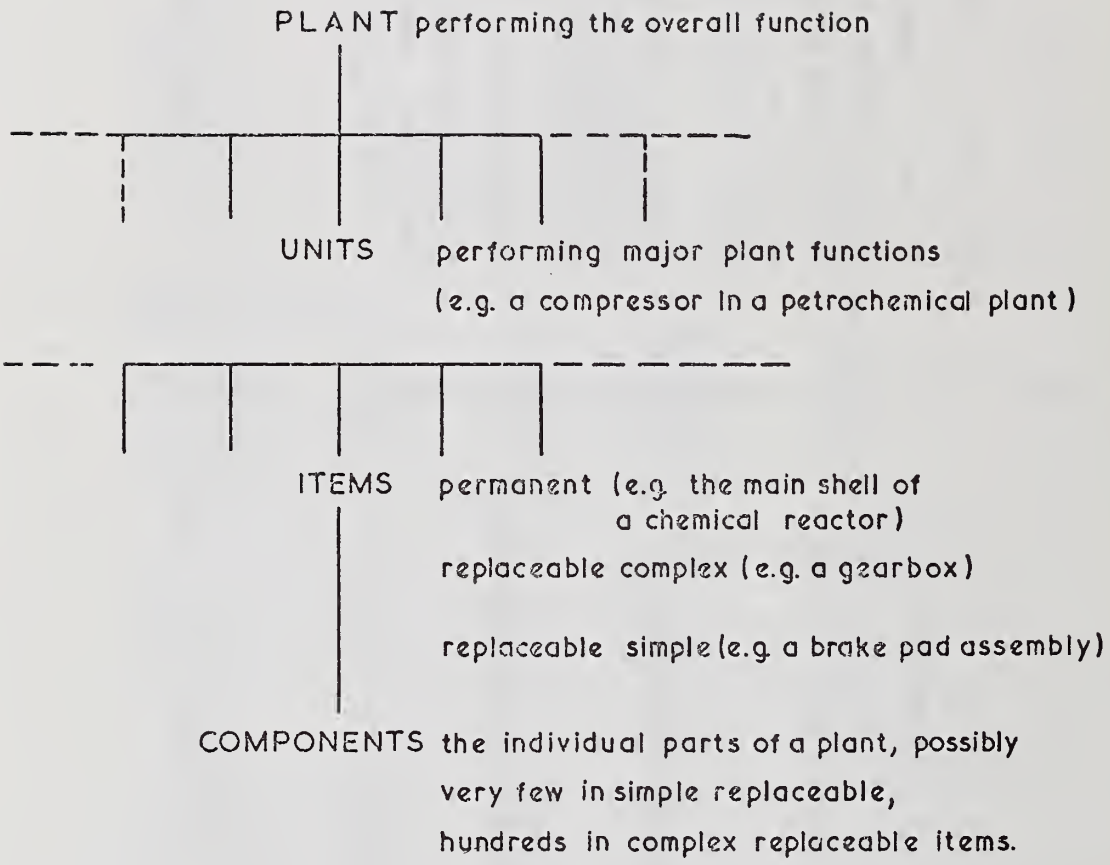


FIGURE 2. PLANT HIERARCHY.

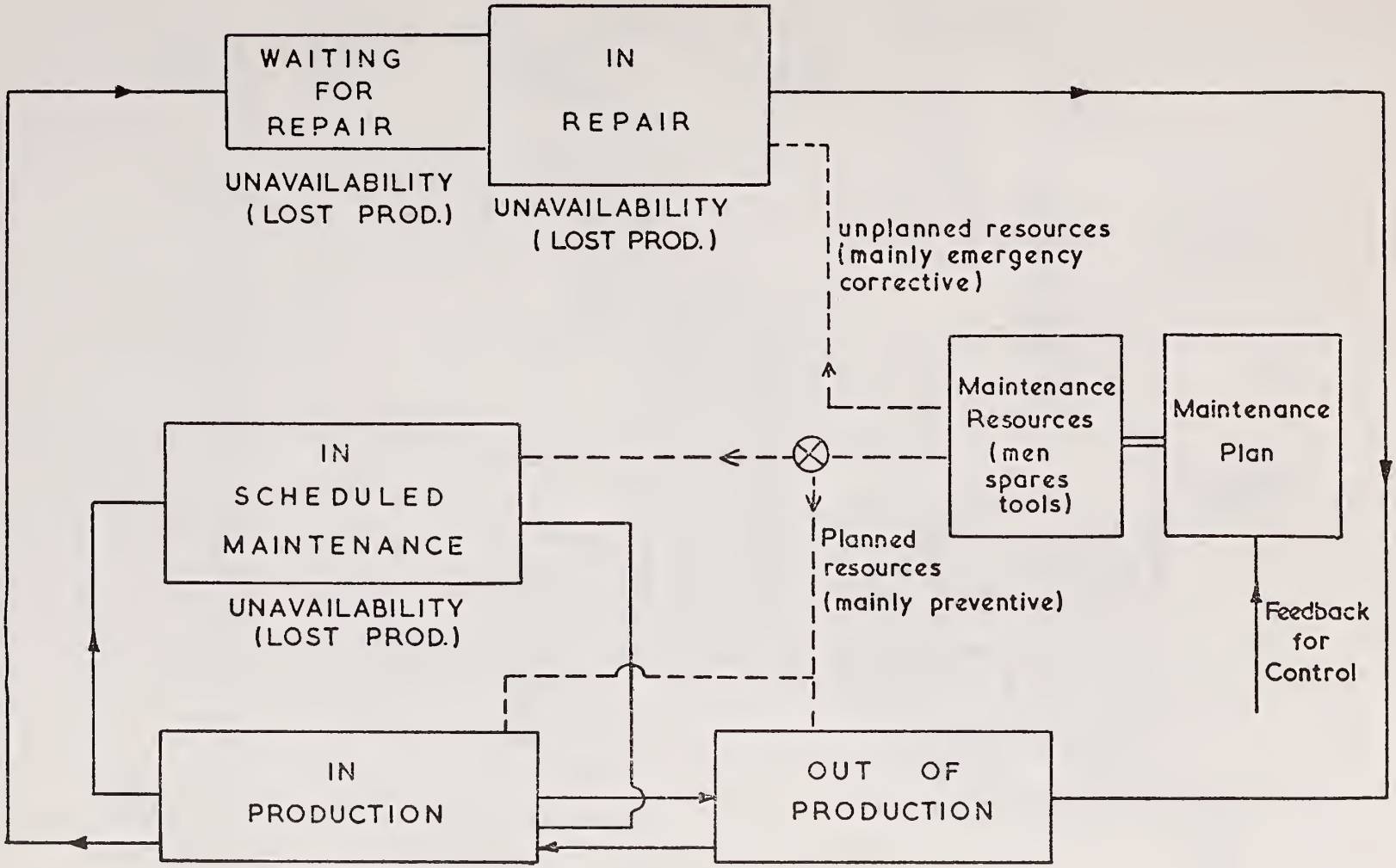


FIGURE 3. THE MAINTENANCE / PRODUCTION SYSTEM.

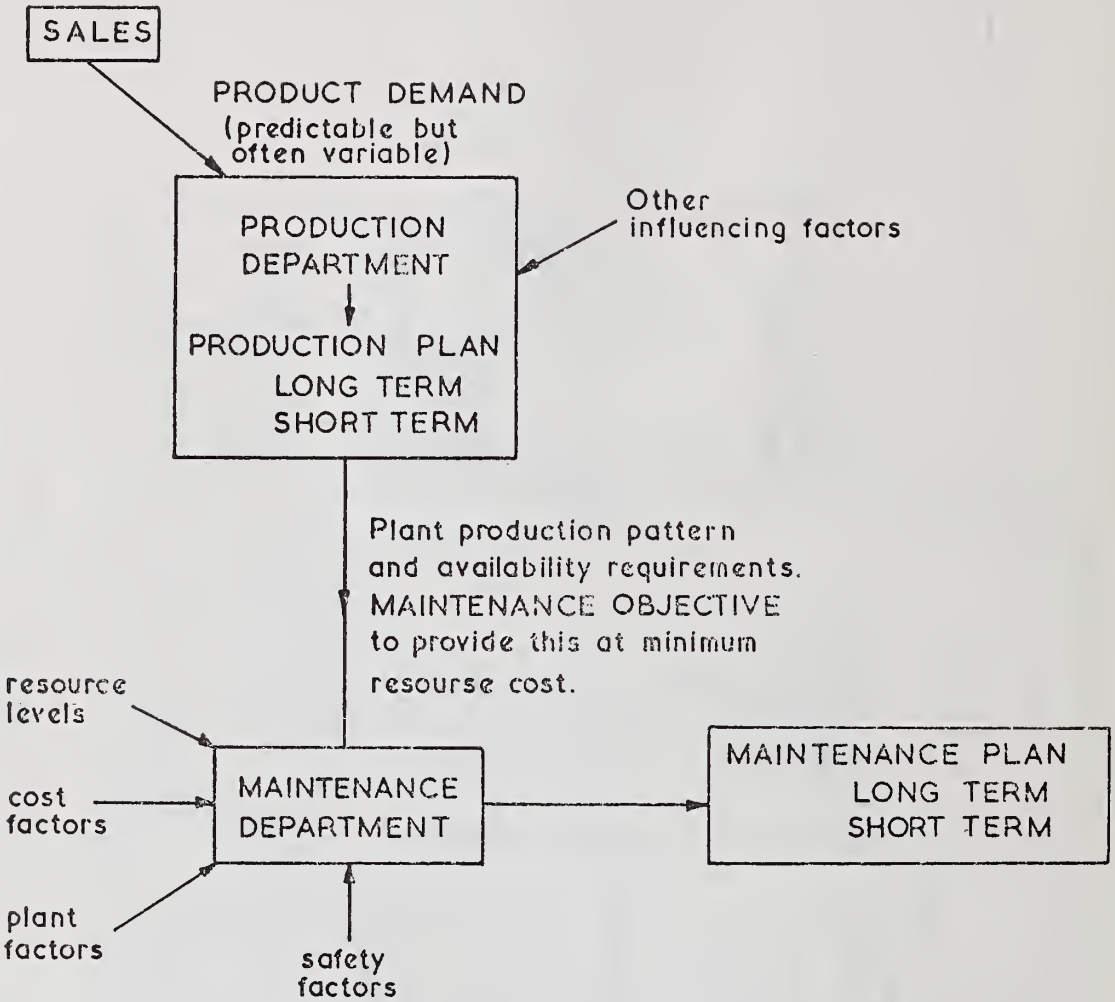


FIGURE 4. THE MAINTENANCE OBJECTIVE.

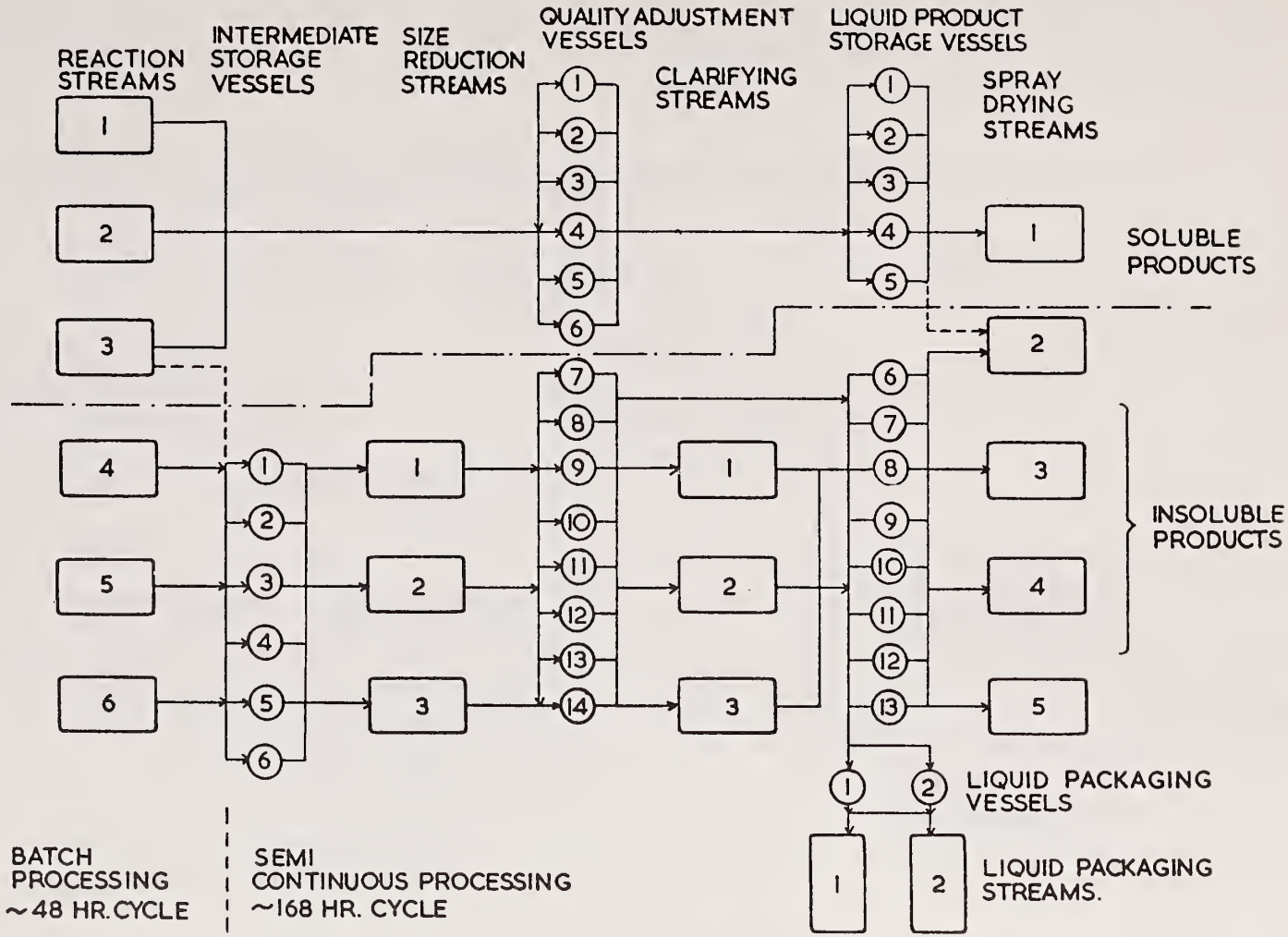


FIGURE 5. SCHEMATIC LAYOUT OF PLANT.

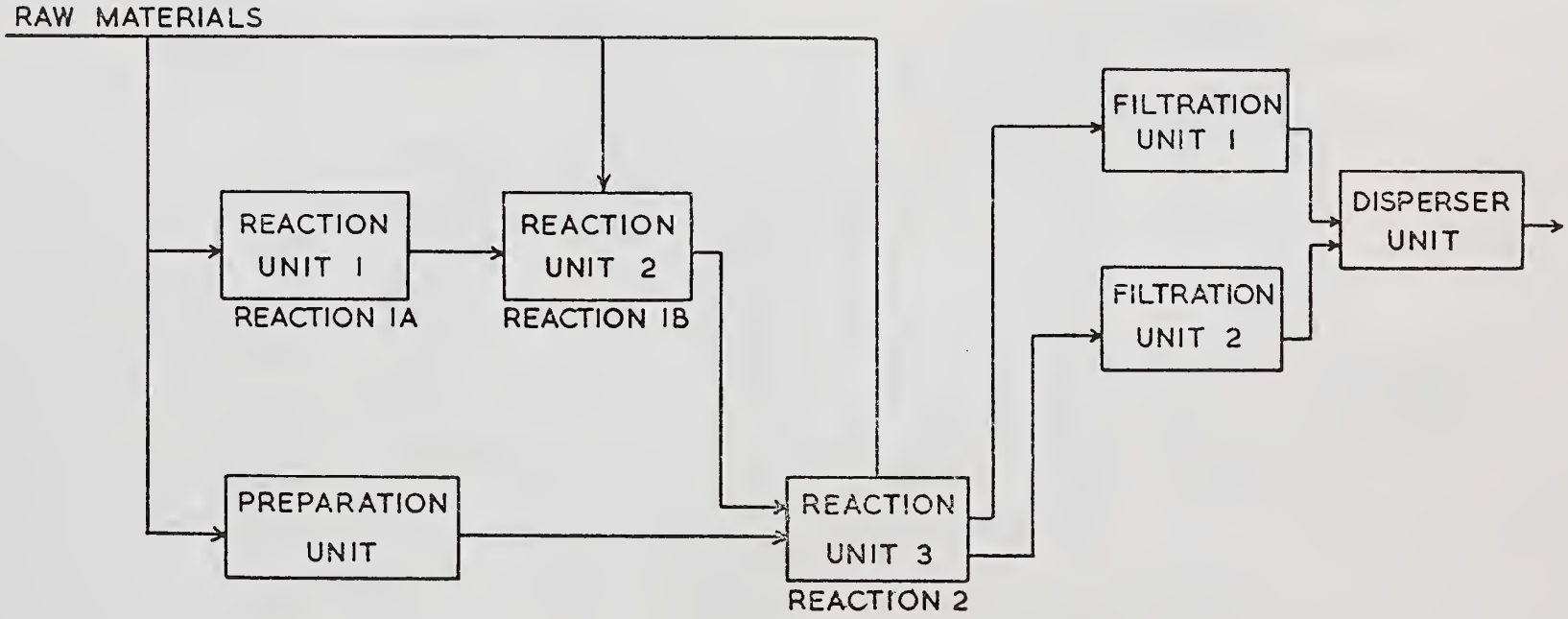


FIGURE 6. ARRANGEMENT OF UNITS IN REACTION STREAM.

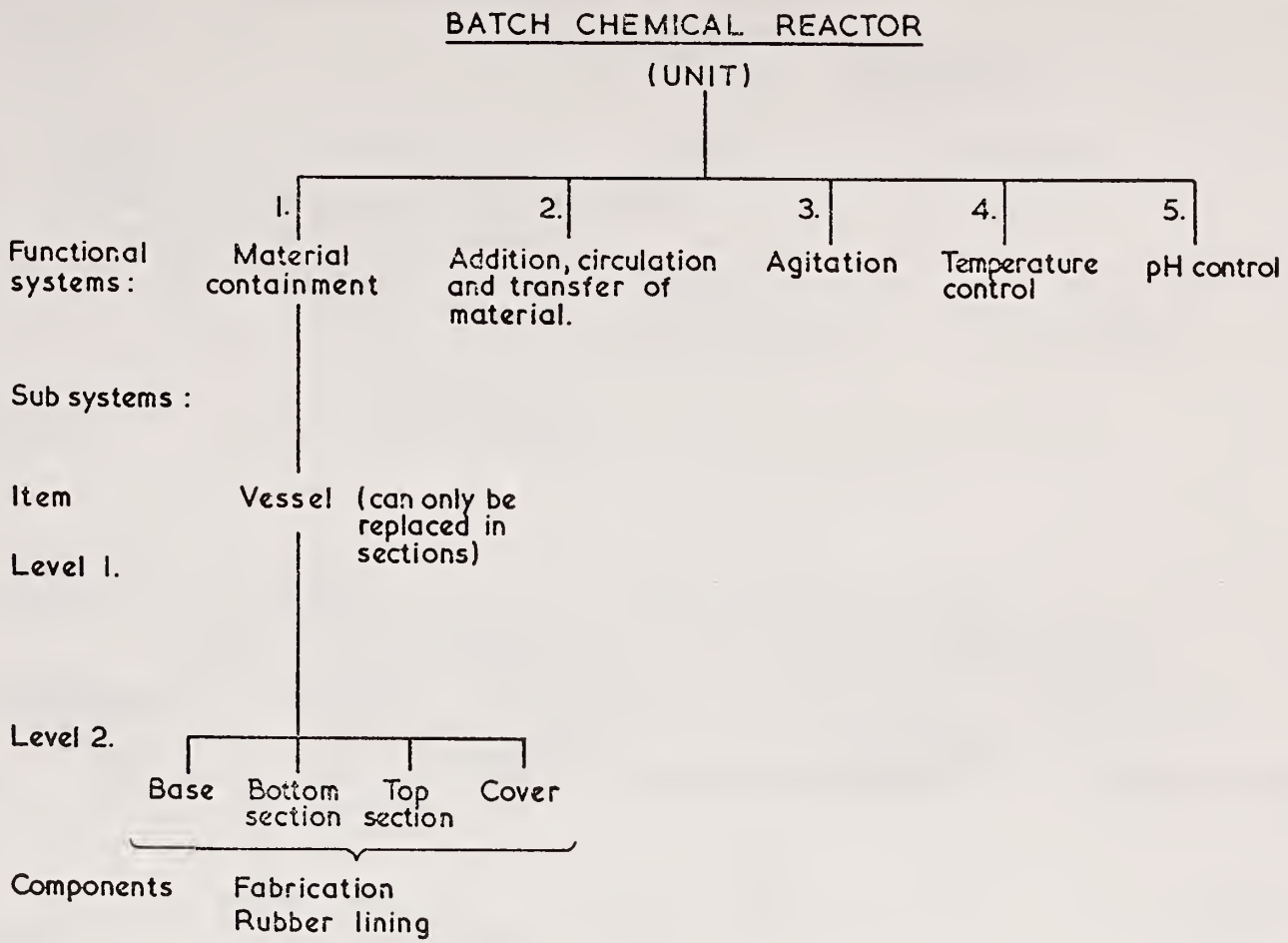
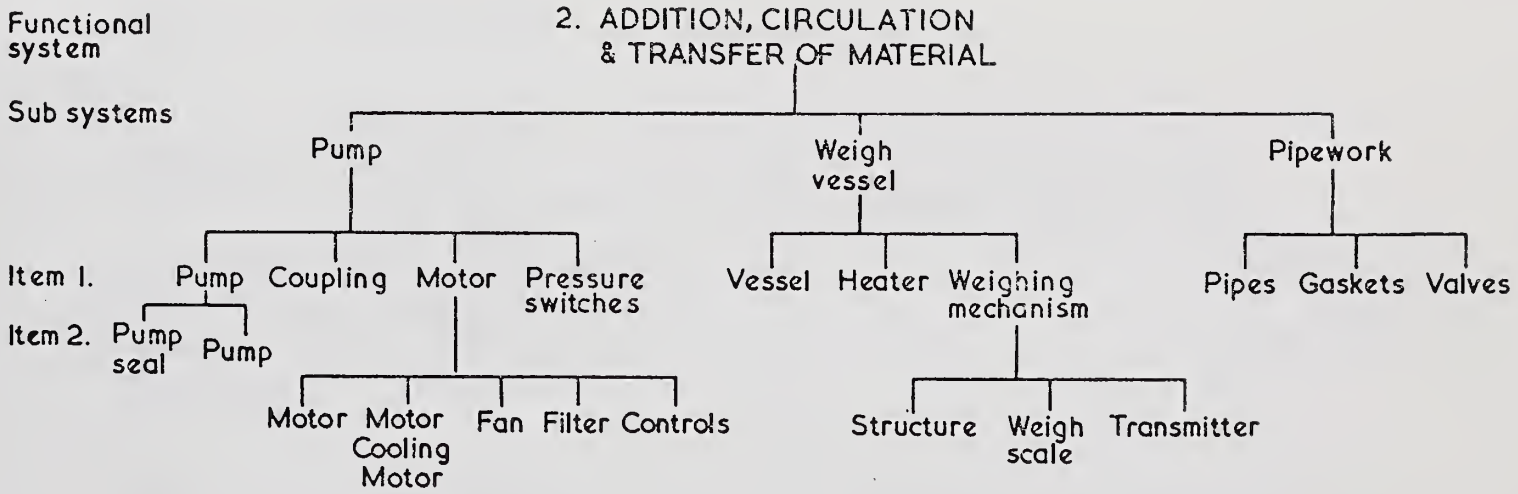


FIGURE 7A. CLASSIFICATION OF ITEMS IN REACTOR.



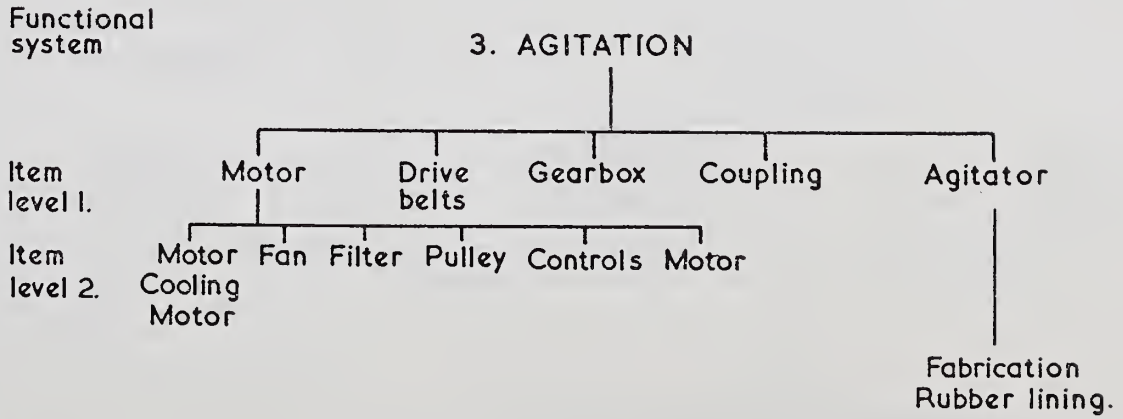


FIGURE 7B. CLASSIFICATION OF ITEMS IN REACTOR

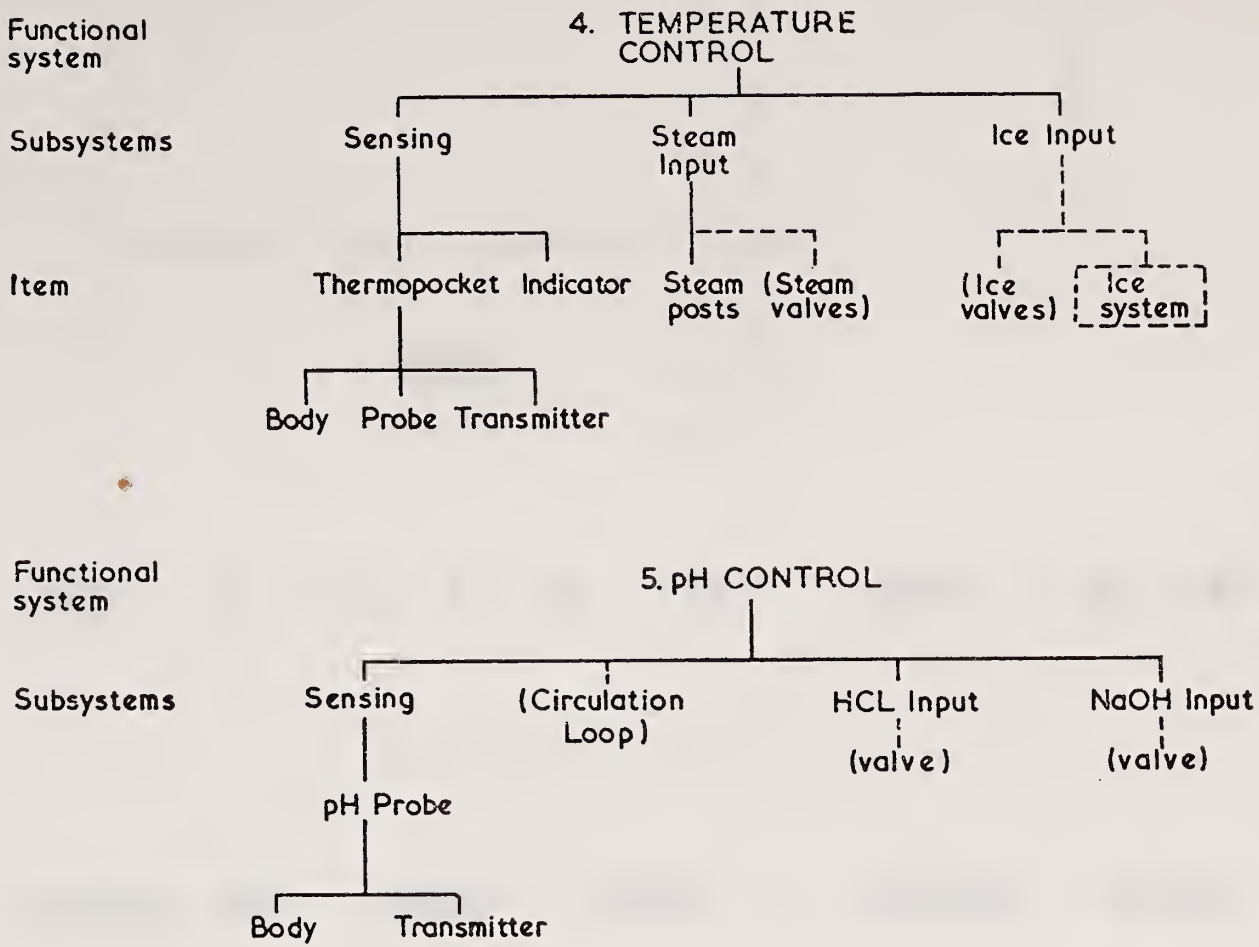


FIGURE 7C. CLASSIFICATION OF ITEMS IN REACTOR.

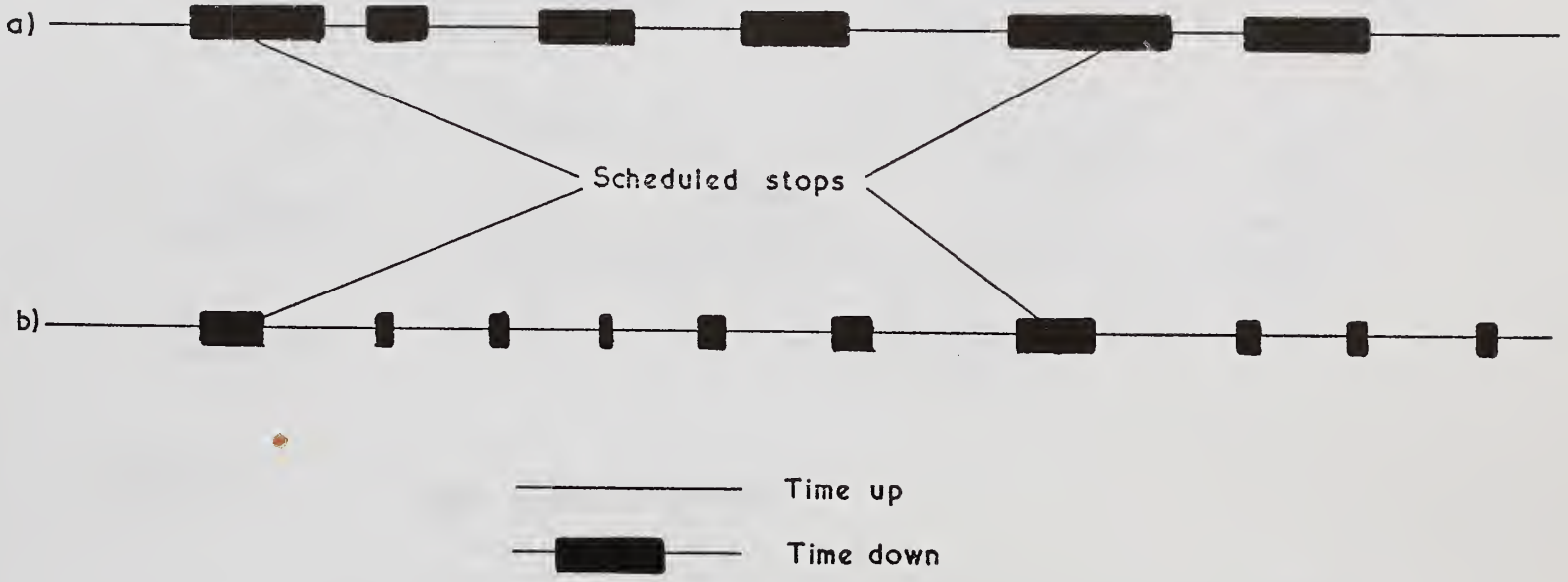


FIGURE 8. PLANT OPERATING PATTERN.

SESSION II

TECHNOLOGY IMPROVEMENTS FOR POWER PLANT APPLICATIONS

CHAIRMAN: K. LUDEMA
UNIVERSITY OF MICHIGAN

IMPROVED ENGINE MAINTENANCE THROUGH AUTOMATED VIBRATION DIAGNOSTIC SYSTEMS

Richard A. Rio
Mechanical Technology Incorporated
968 Albany-Shaker Road
Latham, New York 12110

The rapidly increasing cost of maintenance, the demand for increased equipment utilization, fuel costs, and the difficulty of correctly diagnosing internal mechanical problems in fully assembled jet engines, have stressed the need for more effective engine test equipment. This paper describes the successful application of a component (module) high-speed balancing technique developed for the U. S. Army for use at the Corpus Christi Army Depot and an Automated Vibration Diagnostic System (AVID) for the U. S. Air Force's engine overhaul center at Tinker Air Force Base, Oklahoma. The AVID concept to automate trouble-shooting procedures for fully assembled rebuilt engines is addressed. This system extracts high-frequency vibration data from existing standard instrumentation, thereby providing meaningful mechanical information. A growing appreciation on the part of engine overhaul personnel of the power of automated test equipment has enabled these key features to be combined to reduce operating expenses at engine rebuild facilities.

Key words: Balancing; diagnostics; faults; monitoring; jet engines; overhaul; productivity; vibration.

Significant concern has been expressed in recent years about the relatively high and growing levels of maintenance costs required to keep many kinds of key equipment operational. The aircraft gas turbine engine has been no exception to this trend. Aircraft gas turbine engines have compiled remarkable endurance and safety records over the years, especially given the sophistication of their designs and the rotor speed involved. These records have been and are being earned through expensive and painstaking overhaul practices, applied at regular intervals of operating time. While the costs of this approach have been substantial, the consequences of failure have always far outweighed them. While safety of flight cannot be compromised, future improvements in maintenance engineering can and must be realized to keep the costs of safe operation from becoming prohibitive.

This paper presents two vibration diagnostic techniques which have been developed for the latest jet engine overhaul techniques being developed by the military. These maintenance procedures take advantage of the

latest modular jet engine design concepts.

There are two tiers of maintenance decisions. In the first tier, repair decisions will be performed by the end users at the base installations. Engine components or modules will be returned to the depot for repair and/or refurbishment based upon modifications observed by the user or based upon the established time and cycle limit of that particular module in service. The second tier involves removal of entire engines which are then returned for depot level maintenance. Therefore, both complete engines and discrete engine modules will be cycled through the maintenance facilities.

It will be necessary to have a vibration acceptance test which will certify that repaired engines and modules are acceptable for fleet use. As presented here, a high-speed balancing system will identify potential problems before the module is shipped to the field. For entire engines which require a complete test cell acceptance procedure, an Automated Vibration Diagnostic System (AVID) has been developed which will identify internal mechanical faults using the standard engine vibration sensors.

High Speed Balancing

Rotor balancing is the process of applying a single set of correction weights simultaneously in two or more planes on a rotating shaft to achieve low vibration levels at each measurement location along the shaft, and at a special number of shaft speeds. In its simplest form, this process involves two planes, two sensors, and a single, relatively low speed. In its most complex form, as many as eight or ten balancing planes may be involved, together with an equal number of sensors. As many as six or eight balancing speeds may be required.

When a rotating body remains rigid (i.e., no elastic axis bending, over its entire operating speed range), the simplest, two-plane, low-speed approach can be fully satisfactory. It is this fact which has permitted the governing relationships to be "programmed" in electronic packages as parts of commercially offered balancing machines. What causes difficulty in many cases is the fact that the commercial balancing machine fails to simulate adequately the design operating condition of the component.

The balancing of advanced rotating systems is becoming increasingly difficult with design trends toward lighter, more flexible components which turn at higher speeds. The operating speeds of many systems now being designed are often beyond the first critical. The reason this situation causes concern is that the modes of vibration at the critical speeds often involve significant bending of the system's elastic axis. Since these deformation properties are speed dependent, low-speed two-plane balancing has only limited effectiveness. In fact, such balancing can often make vibration levels worse at the bending critical speeds.

Unfortunately, present-day manufacturing procedures, in spite

of their high-precision nature, leave some distributed residual unbalance in each rotating component. The result is a considerable trial-and-error effort to find a satisfactory balance at the trim-balance stage, and increased efforts toward tighter tolerances and more stringent assembly procedures; all of which can be very costly. As rotors become longer and more flexible, and as lighter weight rotor systems are developed, balancing requirements and methodology must adjust to accommodate them. Problems introduced by disassembly and reassembly are also significant; especially in a gas turbine engine having several disk and blade assemblies, bearings, and a cantilevered turbine.

A procedure for performing rotor balancing in two or more planes, so as to achieve low vibration levels at each of a number of measurement locations and at each of a number of speeds, has been developed. The procedure is conceptually quite simple, and has been designed for operation by technician-level personnel. It may merely be used to supplement the capabilities of a commercially offered balancing machine; or, in its most complete form, it offers the option of replacing a series of two-plane balancing steps by a single multiplane-multispeed balancing of the rotor in its final installation.

In their maintenance philosophy, the military has identified a number of potential advantages in high-speed balancing gas turbine modules.

Cost Savings. It is often extremely complex, time consuming and expensive to high-speed balance an engine while it is installed in a test cell. Quality high-speed balancing of components will often reduce or completely eliminate the need for assembled engine balancing and reduce the rejection rate; thereby saving teardown, reassembly and retest cost.

Improved Rotor Life. If the engine component is flexible (i.e., approaches or traverses bending critical speeds within its operating speed range), high-speed balancing offers unique advantages because of the inability of traditional low-speed balancing to reduce shaft vibrations at these speeds.

Component Diagnostics. Operating component parts at high speeds before assembly to the engine allows a significant degree of component diagnostics (i.e., shift in parts, misalignment, faulty bearings, etc). This, therefore, occurs before the added cost and complexity of installing a complete engine for test and trim balancing.

Accessibility to Problem Component. It is often impractical or impossible to access rotors inside an assembled engine. Accessibility to prescribed balance planes is also often limited because of the "trapped rotor" design of many gas turbine engines. Component "stack up" also makes access to interior shaft components impractical in the assembled engine, but practical in a high-speed balancing module.

Seating of Sub-Component Parts. Operating a component before assembly

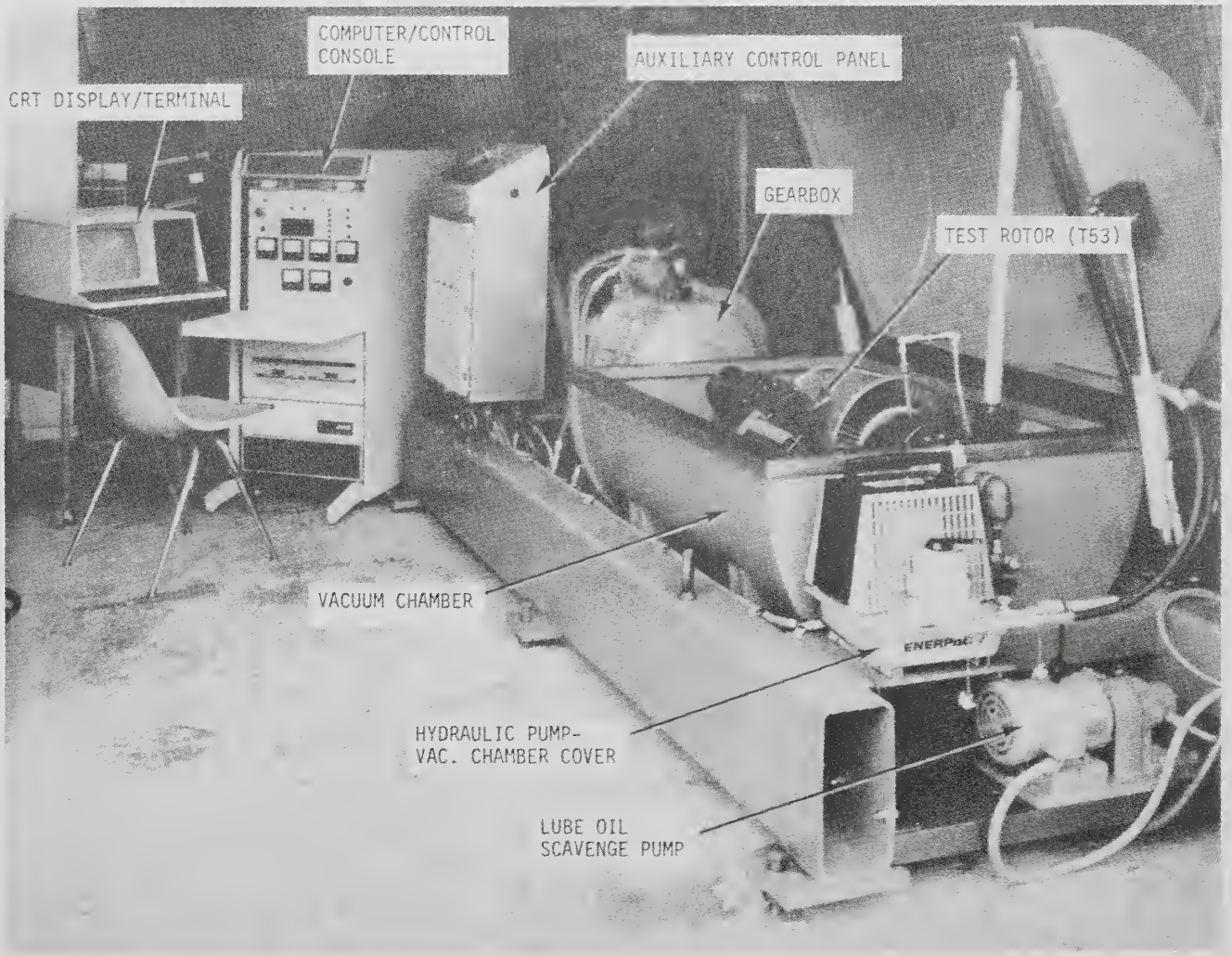


FIGURE I - U. S. Army High-Speed Balancing System - Component Listing

into the engine allows subcomponent parts (i.e., turbine blades, snap fits, etc.), by the action of centrifugal force, to seat in the position in which they will run in an engine. This is especially important in shafts with a high degree of sensitivity to changes in unbalance. Such "run in" of component parts cannot be achieved by only low-speed operation.

Application to United States Army Jet Engines

A system developed for the United States Army permits high-speed balancing of assembled power turbine shafts for both T53 and T55 helicopter engines. Based on an extensive background study, it was determined that one of the power turbines (T53) traverses a bending critical speed well below its normal operating speed in the engine. The other power turbine (T55) traverses a rigid body critical speed and approaches its first bending critical speed at its normal operating speed.

In their present configuration, neither of these engines have the capability to trim balance the power turbine shaft in the test cell. Each vibration-related reject in the test cell requires engine removal and tear down for subcomponent balancing. The engine must then be rebuilt, reinstalled, and rerun in the test cell. The prototype high-speed balancing system allows both T53 and T55 power turbine shafts to be run and high-speed balanced as an assembly before installation into the engine.

Figure 1 shows the major mechanical components of the balancing system. Drive power is provided by a variable-speed electric motor. Speed is increased through a gearbox with output shaft speeds equaling engine operating speeds for the power turbine shaft. The shaft is operated in a vacuum chamber to both reduce the windage (and therefore the amount of drive power required), and to provide for operator safety.

A control console with dedicated minicomputer and CRT terminal is located in a separate control room. An auxiliary control panel mounted on the test stand provides for local low-speed operation and control.

In order to duplicate the dynamic characteristics of the engine installation, engine bearings support structures are used to mount the shaft for balancing. Displacement probes are used to measure shaft deflection. Vibration data are routed to the minicomputer for automatic data acquisition and balancing weight calculation.

Automated Vibration Diagnostics

In several cases, operators of gas turbine engines have begun to adopt the practice of "on-condition" maintenance costs. In the process of this change, the increased emphasis that must be placed on diagnostic systems and procedures has become apparent. These procedures are required to obtain data to determine the presence of a problem, identify trends, and locate the specific faulty component within a fully assembled engine.

Figures 2 and 3 show typical results for high-speed balancing T53 and T55 power turbines using the prototype high-speed balancing system.

Significant technological advances have occurred in recent years in small low-cost minicomputers, digital data processing and filtering, and new methods for using high-frequency vibrations as information carriers. These advances are expected to be of great utility for new monitoring and diagnostic procedures.

The first level of analysis is a comparison of the output signal levels of instrumentation with predetermined limits, such as bearing vibration. The comparison is accomplished by analyzing a number of past readings and permits an initial classification of the machine's condition, such as whether the equipment is operating within safe limits, or whether a large percentage change has occurred in any measured parameter since the last measurement. Presenting this data as a function of time can indicate wear, growing unbalance or component degradation.

Once a signal has been found to be out of bounds, a detailed analysis of the signal and related parameters is initiated. High-speed detailed sampling provides a full-frequency component analysis of vibration. Oil pressure and temperature, and other key static signals are sampled concurrently. This information, together with the operator's understanding of the machinery, will often permit the operator to make a reasonably accurate determination of the probable cause of the observed variance. Typical actions the operator may wish to have the system undertake at this point may include: providing an advisory to circumstances or operating levels; increasing the frequency at which the review of the machine occurs; trending and analyzing measured machine responses for representative past operating history; calculating full-frequency component composition of time-varying signals to identify specific contributing frequencies and amplitudes; and comparing frequency components with stored tables of potential forcing frequencies, such as one-per-rev, gear mesh, etc. The structure of the diagnostic system's logic often permits the maintenance engineering staff to tailor the system to their particular needs.

Analytical and experimental information about the machine may be stored within the system. For example, design data about blading, bearing design, coupling characteristics, critical speeds, and sometimes even analytical equations may be provided. With such information, automated diagnosis is possible. When a machine is overhauled or undergoes maintenance, the details of any observations can be entered into the data base, and the system can categorize experienced changes in behavior with actual physical parameters. Theoretical considerations may be reinforced through operating experience and successful maintenance actions.

As time elapses, the data base assembled through these interactions permits more accurate diagnostic logic to be prepared. The important con-

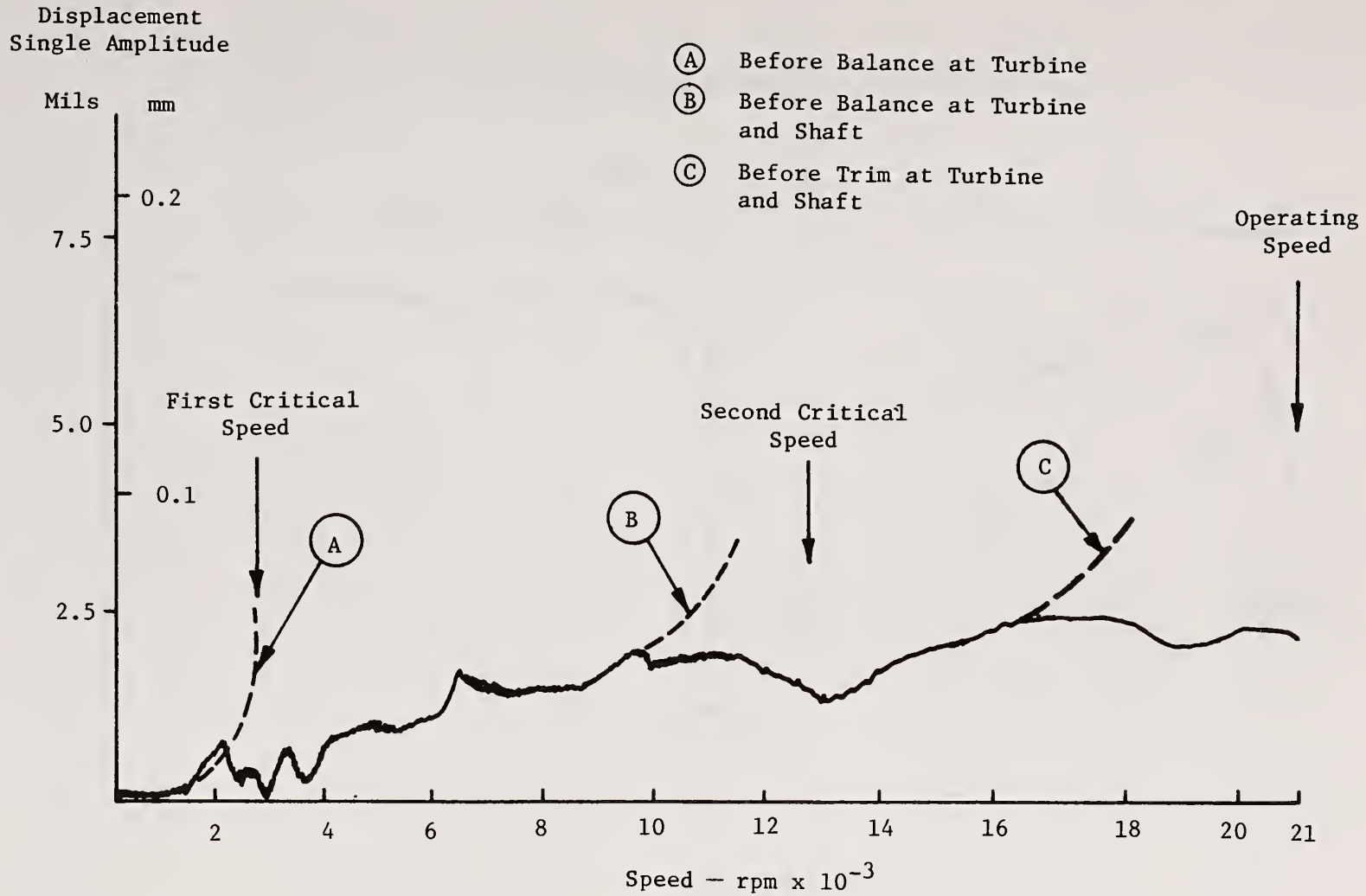


Fig. 2 Results of High-Speed Balancing T53 Power Turbine

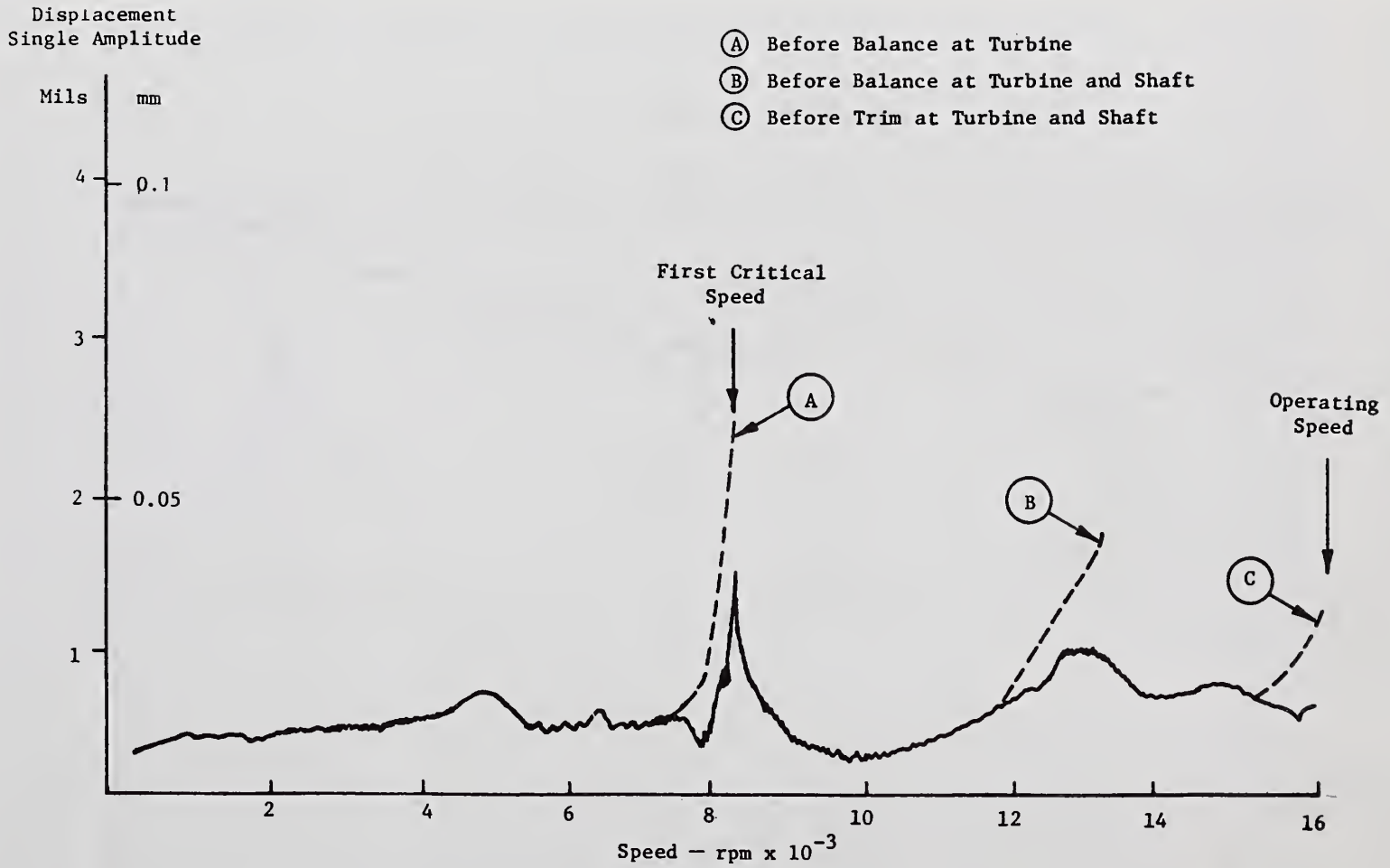


Fig. 3 - Results of High-Speed Balancing T55 Power Turbine

cept in the logic is that the system learns from proven experience and can formally document machine problem histories. Predictive maintenance recommendations are also available. Machinery operating costs can be minimized by providing cost-based logic for accomplishing specific maintenance on only those modules requiring checking. The symptom-fault logic may be asked to identify preventive actions and replacement parts as part of the overhaul process.

Application to United States Air Force Jet Engines

The technologies discussed above have been successfully combined to provide an Automated Vibration Diagnosis System (AVID) for United States Air Force jet engines. The system was installed in four engine test cells at one of the main United States Air Force engine overhaul centers, Oklahoma City Air Logistics Center (OC-ALC). Operation of the equipment by Air Force personnel has demonstrated the practical application of combining minicomputer technology with gas turbine engineering expertise to provide the Air Force with a system which provides fuel savings, increased engine production capacity, and greatly reduced vibration rejection rates.

Overhaul Procedures. Overhaul procedures require that rotating components undergo both static and dynamic balancing during the overhaul process. Engine parts are first weighed and balanced as individual parts, then balanced as assemblies (i.e., compressors and turbines) prior to final assembly. Following final assembly, engines undergo an acceptance test during which critical performance and operating parameters are determined.

During the acceptance test, engines frequently experience vibrations which exceed allowable technical order limits. Depending upon the amplitude, frequency, and location of the vibrations, an engine may be trim balanced while it is on test. If trim balancing is not possible (e.g., vibration not synchronous with rotor vibration, or indicated trim weight too large), then the engine is returned to the final assembly area for corrective rework. Former engine technical order procedures required that three trial trim balance weights be installed separately and the engine operated after insertion of each weight. Data resulting from each run was used to calculate the amount and location of a final balance weight. Approximately eight hours were required to trim balance an engine using this procedure. One major objective of the diagnostic system was to reduce the excessive amount of time required to trim balance the engines.

Engines on which trim balancing was not permissible were returned to the final assembly area with only minimal vibration data available to direct engine rework. Information provided was highly subjective and dependent on test cell operator experience. As a result, rework which was performed on an engine often did not correct the problem, causing the engine to be rejected several times due to excessive vibration levels. Repetitive rework to correct vibration problems results in additional

costs, much of which could be avoided if accurate repair action recommendations were another major objective of the diagnostic system.

Engine rework and test costs are expected to continue to increase as a result of upward trends in manpower and material costs. In addition, the complexity of the new generation of turbofan engines is also resulting in increased maintenance time and costs. These factors, coupled with the requirement for rapid turnaround of engines undergoing overhaul (due to reduced engine inventories) required that a diagnostic system be available to reduce the time required to trim balance, test and provide accurate diagnostic information to direct engine rework.

Automated Engine Trim Balancing Benefits

The TF30 engine was selected for the pilot system demonstration because it is designed for trim balancing and was considered by the Air Force to be a typical engine in its maintenance requirements and vibration characteristics. The engine vibration signals used during acceptance testing were derived from the three standard military velocity sensors normally installed on the engine during test. Before filtering within the vibration amplifier, the signals are routed, along with the speed measurements, to the computer room (see Figure 4).

The TF30 engine AVID System (see Figure 5) consists of six assemblies; the central balancing system, four digital signal processors, and a CRT terminal and hardcopy unit. All of these assemblies are located in a central computer room adjacent to the four test cell control rooms. Each of the digital signal processors is dedicated to monitoring speed and engine vibration signals from one test cell. All the digital signal processors are connected to the central balancing and diagnostic system. The CRT terminal and hardcopy unit are connected to the central balancing system or the digital signal processors. During acceptance testing, the trim balancing system is activated if the engine vibration exceeds the technical order limit. Vibration data is automatically acquired and processed to provide a spectral analysis of the overall signals of the engine's vibration sensors.

The size and location of the required trim balance weight are calculated by the system based on the engine's vibration characteristics. The unique aspect of the trim balancing portion of the AVID system is that trial weight runs are not needed. Engine sensitivity data, also known as influence coefficients, are stored within the minicomputer system. These data are then recalled and processed with the dynamic response of the engine on test to calculate the proper correction weights.

During a verification test period, ten TF30 engines were trim balanced. Trim balancing was successful in all cases. The engines were trim balanced using the influence coefficient method and the engine vibrations were reduced to a level below the technical order specifications. Engines are now routinely trim balanced by Air Force maintenance personnel. The average time to trim balance has been reduced to 1 hour and 20

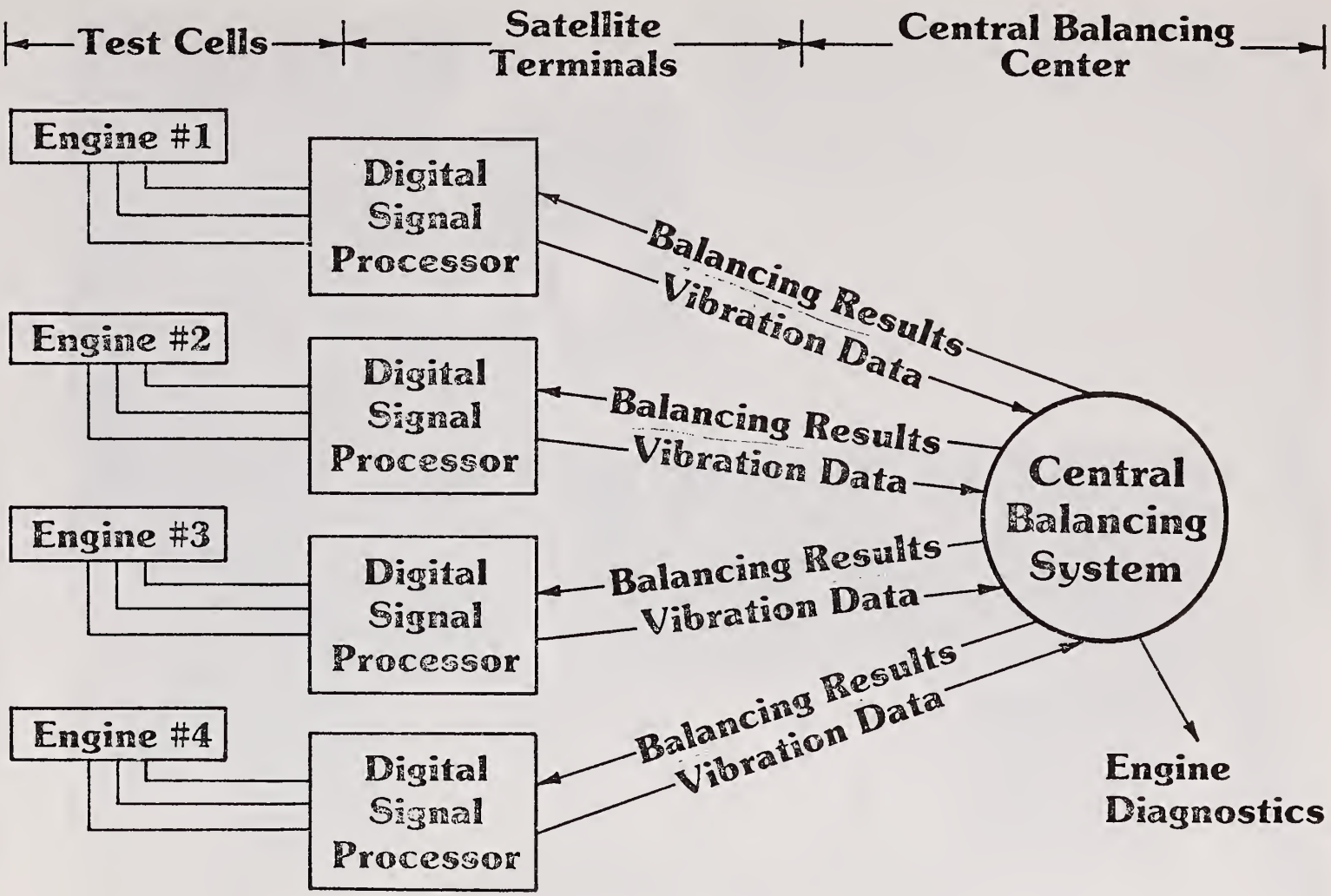


Fig. 4 Schematic of an Engine Trim Balancing and Diagnostic System

Fig. 5 TF30 Engine Avid System

minutes, compared to the original 8 hours. Test cell time per engine was thus reduced by about 80% for the trim balancing operation, with attendant savings in fuel usage and increases in engine production rates.

Automated Engine Condition Diagnosis Benefits

The key principles of the vibrations diagnostic system operation are based on engineering experience in machinery dynamics. This experience has shown that dynamic observation, particularly of rotor and casing vibrations, is an excellent method to identify existing or impending problems. The complex raw signal data can be processed to provide reliable information that permits the evaluation and pinpointing of the problem source. These diagnostic elements have been combined into systems for making accurate decisions once suitable levels of vibrational characteristics have been defined. The AVID system minimizes the decisions required of the operator and offers rapid identification of problems. The system samples the outputs of the standard existing engine vibration sensors in a logical sequential manner to arrive at a decision as to the condition of the engine under test.

The engine condition diagnosis system acquires both synchronous and non-synchronous vibration signatures from engines in all four test cells. The system conducts an analysis of each engine's vibration response and produces a hardcopy printout indicating the cause for high vibration, numerically ranked from highest to lowest severity. The TF30 engine Symptom-Fault Matrix, based upon existing data and upon pre-programmed engineering knowledge of the engine, identifies the engine faults. Malfunctions are identified in the order of severity. This unique system feature makes use of general symptom-fault relationships for gas turbines, with specific experience probabilities for the TF30 engine. The diagnostic printouts indicate those faults which should be corrected. These data provide guidelines to the maintenance staff and help establish rework priorities.

Vibration diagnostics were performed on ten TF30 engines during a verification test period. To document the accuracy of the predicted engine faults, maintenance action worksheets accompanied the engines that were rejected for vibration-related malfunctions. Successful correlation between the AVID System's diagnostic summaries and the actual maintenance required by the engines has provided verification of the TF30 vibration diagnostics. The verification test included TF30-P7, TF30-P9, and TF30-P100 engines. The diagnostic system proved nearly 90% accurate (20 out of 23 cases).

In addition, the system maintains an archive of engine data:

- Stored signatures of rejected analysis
- Stored signatures of average engines
  - Overall vibration

- N_1 and N_2 components versus speed
- Spectral plots
- Six-month sampling (continuously updated)

- Engine serial numbers tracked for short term
  - Repeat rejects identified
  - Engine corrective maintenance history compiled
- Six-month interval of good engine data
  - Overall vibration
  - Retrieval data on earlier rejects

Automated Engine Performance Diagnosis Benefits

In addition to vibration-related engine rejections, a significant portion of post-overhaul rejections are caused by gas-path performance problems such as low thrust, high exhaust gas temperature and high specific fuel consumption. A methodology is being developed (Ref. 1) to increase the acceptance rate of overhauled J75-P-17 turbojet engines. To avoid engine modification, a minimum number of additional sensors were installed to diagnose faulty components from the performance signature. A computer simulation was also developed to identify the faults and to calculate the beneficial effects of easily installed changes or replacements of components. Gas-path performance diagnosis is planned for implementation on the installed AVID system. Static channels such as those for pressure and temperature will be incorporated into the symptom-fault logic to expand the system capability.

Summary and Conclusions

Automated systems for balancing and diagnosing engine faults has been designed, developed, and successfully demonstrated in production jet engine overhaul facilities.

Quality high-speed balancing of components will often reduce or completely eliminate the need for assembled engine balancing and reduce the reject rate, thereby saving teardown, reassembly, and retest costs.

Stored engine sensitivity data can be used to calculate single-shot balance weights which, when installed, bring the engine vibration down to acceptable levels. This process has eliminated the need for trial weights and average trim balance time has been reduced from between 7 and 8 hours to 1 hour and 20 minutes through the use of this system.

An automated diagnostic system which uses only vibration data from standard sensors has successfully predicted faults within the engine. During a verification of the system's diagnostic capability, nine engines were torn down and inspected with 90% accuracy of predicted engine faults.

Based upon fuel savings, increased engine production capacity, and reduced vibration reject rate, the installed trim balancing and diagnos-

tic system is projected to yield a multimillion dollar cost savings in its first year of operation.

Air Force maintenance personnel are routinely operating the trim balancing and diagnostic system without additional skilled personnel during normal engine acceptance testing.

The AVID System can be expanded to include gas-path performance diagnostics, and with field-level communication and data processing, should provide a practical method of engine health accountability during the entire life of the engine.

Reference

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INNOVATIONS IN EPICYCLIC GEAR SYSTEM DESIGN FOR INCREASED SERVICE LIFE

D. E. Pauze
US Army Aviation Research and Development Command
Propulsion Laboratory
Lewis Research Center
Cleveland, Ohio 44135

Abstract: Current epicyclic gear systems in helicopter drive trains are designed for a non-catastrophic failure mode: surface fatigue. The sun and ring gears are loaded on one side of the gear teeth only, so that otherwise perfectly good gears are retired from service. With design innovations, the epicyclic gears can be made with fore and aft symmetry to perform double duty.

Key words: Bearing life; bearings; epicyclic system; gear train; planet bearings; planetary gears.

When aviation was in its infancy, the propulsion system for aircraft consisted of a propeller driven by a reciprocating engine. The thrust requirements were low because the aircraft was small and low-speed. The small propeller could be direct drive at engine speed without exceeding the propeller's limit in tip speed. As aviation technology advanced, the aircraft grew in size and speed, and the propeller became larger to provide the higher thrust required, its RPM reduced to maintain tip speed. Meanwhile, engine RPM was increased to improve the specific weight (lb/hp) and specific fuel consumption (lb per hr/hp). At that time, propeller speed decreaser gear was introduced, and was made integral with the engine.

With the advent of the aircraft gas turbine, the need for propellers and their speed decreaser gear dramatically changed. The pure-jet airplane (fixed-wing aircraft powered by a turbojet engine) required no propeller whatsoever, while the prop-jet airplane (fixed-wing aircraft powered by a turboprop engine) continued to use a propeller and speed decreaser gear. Since the pure jets far outnumbered the prop-jets, the number of speed decreaser gears flying in the world would have been significantly reduced except for another change.

The third type of aircraft gas turbine, the turboshaft engine, provided a significant improvement in specific weight which equated to a jump from less than one to more than three horsepower per pound of engine weight. This breakthrough made the helicopter practical. The

slack in the use of speed decreaser gears created by the pure jet was picked up by the helicopter, so that the speed decreaser gear is still important in aircraft applications.

Figure 1 shows a typical helicopter arrangement of drive train with twin engines. This is a composite of several installations. The power turbine in the turboshaft engine is a free turbine which feeds power through a right-angle drive gearbox into a transmission. The outputs from the transmission are: the main rotor, airframe accessory drives, and tail rotor. The tail rotor drive includes an intermediate gearbox and a tail rotor gearbox.

The gear arrangement in this typical helicopter drive train is shown in schematic form in Figure 2. The epicyclic gear system is the final reduction in the main rotor drive, and the axes of these gears are vertical or near vertical. Shown here is a large helicopter. There is an earlier small helicopter which incorporates a two-stage planetary reduction driven by a single engine.

Figure 3 shows the drive system schematic of an existing tandem rotor helicopter. This one uses a two-stage epicyclic gear system in the final reduction of each rotor. Figure 4 shows the drive system schematic of a turboprop engine. Again, the epicyclic gear system is the final reduction of the speed decreaser gear. In this case, the first-stage reduction provides an offset so that the propeller is offset from the engine centerline. This offset provides a cleaner inlet to the engine.

The reciprocating engine and the gas turbine for aircraft share a common trait in their speed decreaser gear. They both use the epicyclic gear system, but there the similarity ends. The reciprocating engine is essentially a low-speed (RPM) machine, while the gas turbine is high-speed. The difference in reduction ratio is significant, and is manifested in the evolution of the epicyclic gear arrangement as shown in Table I.

Referring to Table I, consider the 1950 and 1980 meshing frequencies of the sun gear relative to the planet idler. Their actual disparity in operation is greater than the calculated 3.0 vs. 6.5 or 2:1. The sharing of the load among the planet idlers was and is dependent on the manufacturing error in tooth-to-tooth spacing. In 1950, that error was in the neighborhood of 0.0005 inch; in 1980, 0.0002 inch. Translated into terms of load sharing, in 1950 one could expect approximately 1/3 of the total number of planets to share the load at any given moment. In 1980, that fraction is slightly more than doubled. Adjusting the relative meshing frequencies for load sharing, the 1950 figure becomes approximately unity, and the 1980 figure becomes approximately 4.5. Their actual (adjusted) disparity becomes 1.0 vs. 4.5 or 4:1. Therein lies the concern for the sun gear in today's helicopter. It is using up its surface fatigue life at many

times the rate of its mating gears.

Figure 5 shows graphically the large difference between the epicyclic gear arrangements in the speed decreaser gears, then and now. The explanation lies in the nature of the prime movers:

Aircraft		
Type	Airplane	Helicopter
Vintage year	1950	1980
Speed Decreaser Gear (SDG)		
Rating, Approximate	3500 Hp	3500 Hp
Supplied by	Engine Mfr	Airframe Mfr
Driven by	One Engine	Two Engines
Engine		
Type	Reciprocating	Gas Turbine
Power to Weight Ratio	1:1	4:1
Input Shaft to SDG	Crankshaft	Power Turbine
Input Shaft Speed	Low	High

Naturally, the epicyclic gear system did not make this large change in one jump. Figure 6 shows some selected interim arrangements. The 1960 helicopter was powered by a single engine, the 1970 helicopter by two engines. The evolution of aircraft epicyclic gear systems shows a distinct trend of higher reduction ratios, which is a direct result of the evolution of turboshaft engines. The engine trend is to smaller, higher-speed engines. This is in keeping with the square-cube law. Recall the horsepower per pound of engine weight previously mentioned. Horsepower is a function of mass flow (W_a) in the engine which is directly proportional to the inlet cross-sectional area (L^2). Weight is a function of volume (L^3). The natural corollary is the trend to smaller engines and multi-engine installations. The latter provided another benefit for helicopters: one engine inoperative (OEI) capability.

Since a discussion of epicyclic gear systems would be incomplete without turboprops, Figure 7 touches on this application. The 3-planet epicyclic gear system is probably beyond the practical limit, the sun gear being very small. The planetary reduction ratio of $1 + R/S = 13$ is attractive, but the relative meshing frequency of $n.P/S = 16.5$ is not. All of the epicyclic arrangements shown in Figures 5 through 7 have full-depth teeth with minimum clearances between planets. These are high-density gear sets, much favored by gear designers.

Figure 8 is a graphic representation of the trends in planetary reduction ratios and sun gear meshing frequencies. These are diverging curves, with the latter rising more rapidly than the former. A star arrangement would displace the lower curve by one unit, but the slope would be the same.

Figure 9 describes the two families of epicyclic gear systems: planetary and star arrangements. Their names have their origin in astron-

omy; planets orbit about the sun, and the stars are fixed relative to the sun. Both arrangements have been used in aircraft applications, but the planetary system is by far the more popular. The reason is obvious: the gear designer obtains an additional unit of reduction ratio with the same size star arrangement. The epicyclic gear systems are also attractive for other reasons. Their high reduction ratios fit well with high-speed aircraft gas turbines. Their multiple load path provides a compact, high-density gear set which is lightweight and of low volume.

The design constraints in epicyclic gear systems for aircraft applications are formidable. The system is designed for a non-catastrophic failure mode: surface fatigue. The accent is on weight and volume. Cost and the "ilities" (producibility, affordability, availability, reliability, maintainability, vulnerability, and survivability) are important considerations, too. However, the designer's first hurdle is weight and cost. To avoid the unpleasant prospect of a good engine dragging an inoperative engine, an over-running clutch is provided in the drive system. The helicopter is essentially a constant-speed machine while the turboprop is variable speed. For reverse thrust, the propeller goes into reverse pitch, with the engine driving as in forward thrust.

What are the pacing items in epicyclic gear system life? The sun gear has the shortest gear life, and the planet bearing has the shortest bearing life. The planet gears and ring gears follow in that order. As previously mentioned, the gear mode of failure is surface fatigue of the gear teeth. The planet bearing mode of failure is surface fatigue of the inner race.

For a better understanding of epicyclic gear systems, let us consider the applications of load and those features which will "respond to treatment." The sun gear has many more applications of load than its mating gears by the ratio of n.P/S. It drives on one side of the gear teeth only - recall the over-running clutch. The planet bearing "sees" double the useful, transmitted load, a condition which is inherent in an idler bearing. The inner race is fixed in the carrier, with the outer race rotating. (In many cases, the outer race is integral with the idler gear.) Being fixed, the bearing inner race is loaded on one half of the circumference only. The planet gear teeth are subjected to reverse bending, a condition also inherent in an idler gear. In addition, the unit (contact compressive) stress is higher with the sun than with the ring gear. Like the sun gear, the ring gear teeth are loaded on one side only.

In the area of gear life, there is not 100% agreement among the helicopter manufacturers. One claims his gears have infinite life, that his gears are replaced only when abused. Another calculates surface fatigue life in accordance with AGMA Standards, ostensibly to replace

the gears when their calculated life is used up. All recommend stocking spares. A frequent mode of failure is reported to be scoring, which is due to overtemperature and/or overtorque, oil interruption, or loss of lubricant. Current practice calls for replacing "failed" gears with new ones, so that otherwise perfectly good gears are retired from service.

Any criticism, however constructive, should be followed by a suggestion of a better way. The change proposed herein would provide for double duty of the epicyclic gears and planet bearings. The change would provide fore and aft symmetry in the affected parts for reversibility in service. Some of the parts affected already have that capability. A limited survey of the field disclosed the following:

	Currently in Use	
Item	Fore & Aft Symmetry	Part Reversed In Service
Sun Gear	No	No
Planet Gear	Yes	No
Planet Bearing	Some	Some
Ring Gear	Some	?

The sun gear would require special treatment in the helicopter application. The main rotor shaft is inside the sun gear to provide the maximum possible bearing span for the main rotor bearings. These bearings straddle the sun gear and collector gear (bevel gear driven by both engines of a twin-engine helicopter). Therefore, Figure 10 shows the sun shaftgear with an external spline which provides the maximum gear ID.

The turboprop sun gear and some large sun gears in helicopters could accommodate an internal spline which has the advantage of minimizing the additional length needed to accept the fore-and-aft locking device between the separable sun gear and shaft. Figure 11 shows an internal-external snap ring. This arrangement is akin to a piston ring. The difference is that the "cylinder" has an internal groove into which the snap ring expands during assembly. The sun gear incorporates four radial holes equally spaced at the snap ring groove for disassembly.

Figure 12 shows a ring gear for a 2-stage planetary gear set in an existing helicopter. The manufacturer achieved low cost by providing identical epicyclics in both stages, thereby opening up the possibility of a reversible gear for double duty. There would be no increase in cost, in this case, but an increase in weight.

Figure 13 identifies the assembly/disassembly tools required for the reversible sun gear which uses the internal-external snap ring. There is no need to show the assembly tool. It is a piston ring compressor

which is commercially available. The disassembly tool is a ring with four radial screws, equally spaced. These screws would be positioned over the radial holes in the sun gear which are located at the internal snap-ring groove. They (the screws) would be turned in sequentially to press the snap ring out of internal groove preparatory to disengagement of the sun gear from its shaft. The latter operation would be accomplished in an arbor press.

The change proposed herein is not 100% gain; it is a tradeoff. For a small increase in weight and flyaway cost, save in the cost of spares. Of course, this change would have to begin with design and be implemented in the field. However, the helicopter manufacturer's primary concern in the area of cost is to be competitive in flyaway cost; there is no incentive to increase flyaway cost now with the prospect of recovering that cost in spares sometime in the future. Therefore, a double-duty epicyclic system would probably have to begin with the Government specs accompanying the RFP/RFQ for new helicopter systems. Here again, the Government is inhibited by affordability, the cost of acquisition.

There is another consideration, the intangible benefits to the user. If and when the U.S. Army's helicopters are used in war, the lessons of the last high-intensity conflict can be expected to be re-learned, that there are never enough spares on hand. Whatever the intensity of the conflict, there will be combat damage; there will be loss of lubricant and/or loss of lube pressure. The double-duty epicyclic system could enhance the availability of helicopters by reducing the incidence of AOCP (aircraft out of commission for parts) on account of slight but otherwise disabling damage to one side of gear teeth and/or to one-half the circumference of a planet bearing inner race.

EVOLUTION OF EPICYCLIC GEAR SYSTEMS
AIRCRAFT APPLICATIONS

ENGINE		EPICYCLIC GEAR SYSTEM		
TYPE	IOC DECADE	$\frac{R}{S}$	η	$\eta \frac{P}{S}$
RECIPROCATING	1950	1.3	20	3.0
TURBOSHAFT	1960	2.1	8	4.4
TURBOSHAFT	1970	2.8	6	5.4
TURBOSHAFT	1980	3.6	5	6.5
TURBOPROP	1960	5.4	4	8.6

MESHING FREQUENCY OF THE SUN GEAR RELATIVE TO PLANET IDLER:

$$\frac{f_S}{f_p} = \eta \frac{P}{S}$$

WHERE η = NUMBER OF PLANET IDLERS
P = NUMBER OF TEETH IN PLANET IDLER
R = NUMBER OF TEETH IN RING GEAR
S = NUMBER OF TEETH IN SUN GEAR

TABLE 1.

HELICOPTER PROPULSION ENGINES AND DRIVE TRAIN

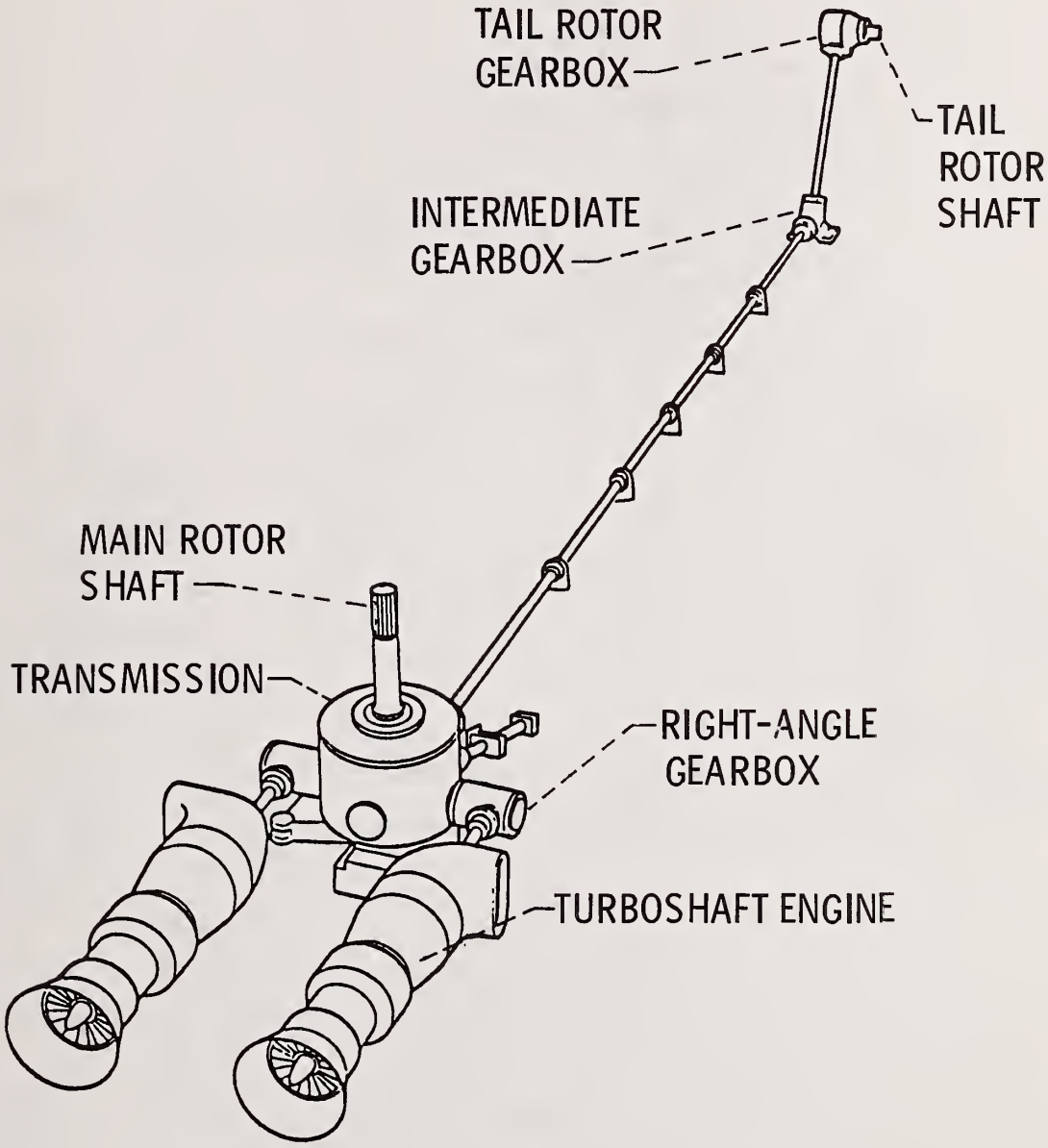


FIGURE 1.

DRIVE SYSTEM SCHEMATIC
SINGLE-ROTOR HELICOPTER

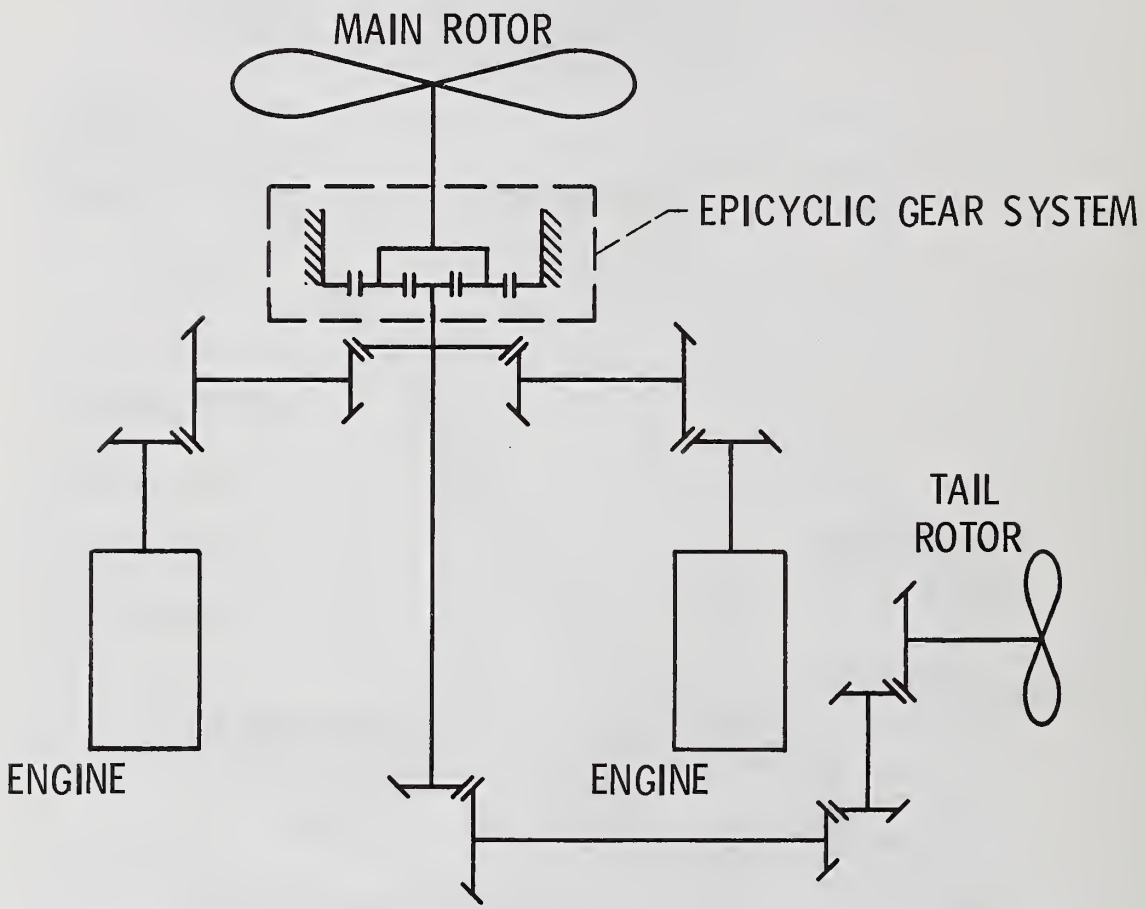


FIGURE 2.

DRIVE SYSTEM SCHEMATIC

TANDEM ROTOR HELICOPTER

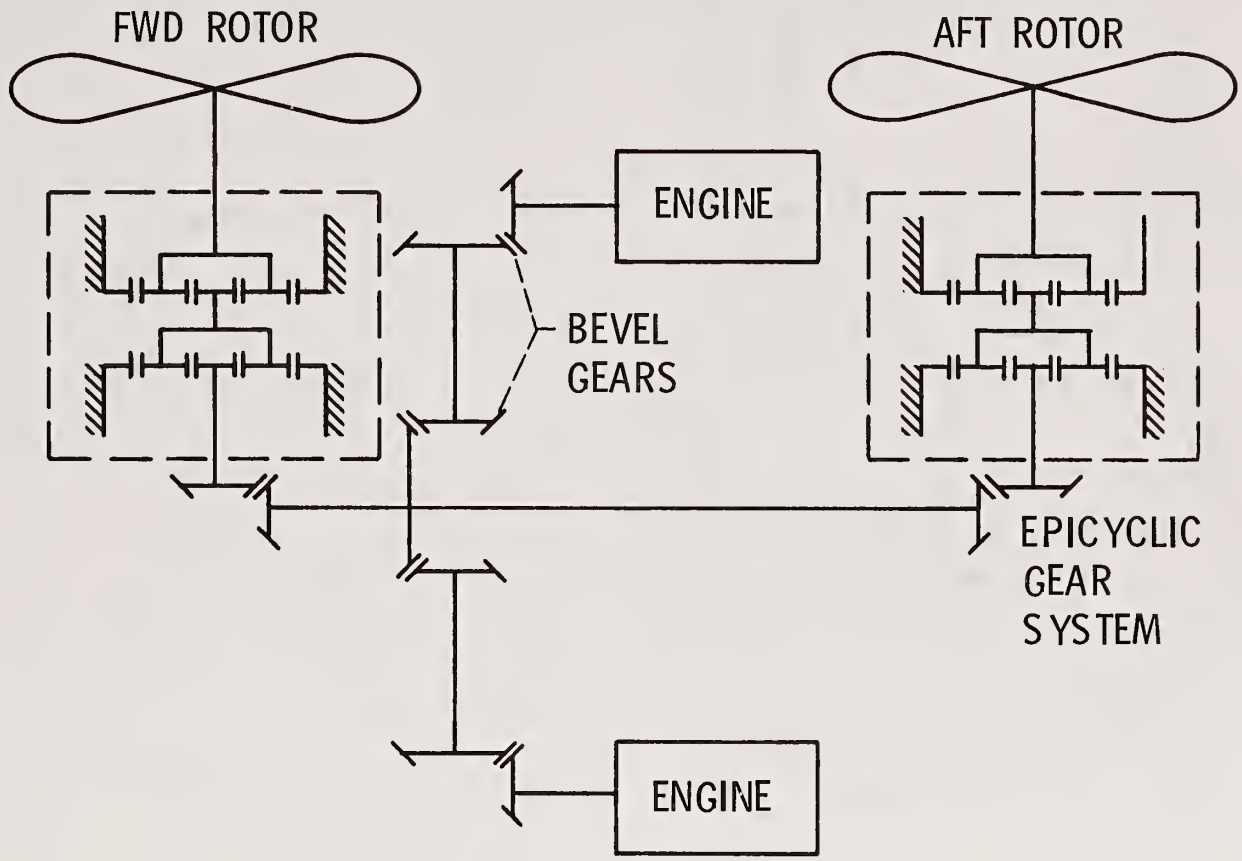


FIGURE 3.

DRIVE SYSTEM SCHEMATIC

TURBOPROP

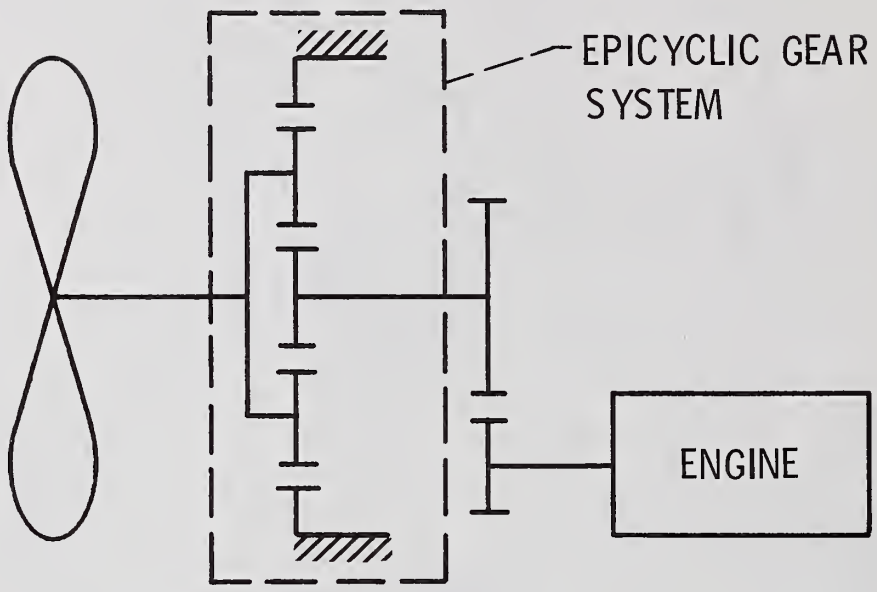


FIGURE 4.

EPICYCLIC GEAR ARRANGEMENTS – THEN AND NOW
AIRCRAFT APPLICATIONS

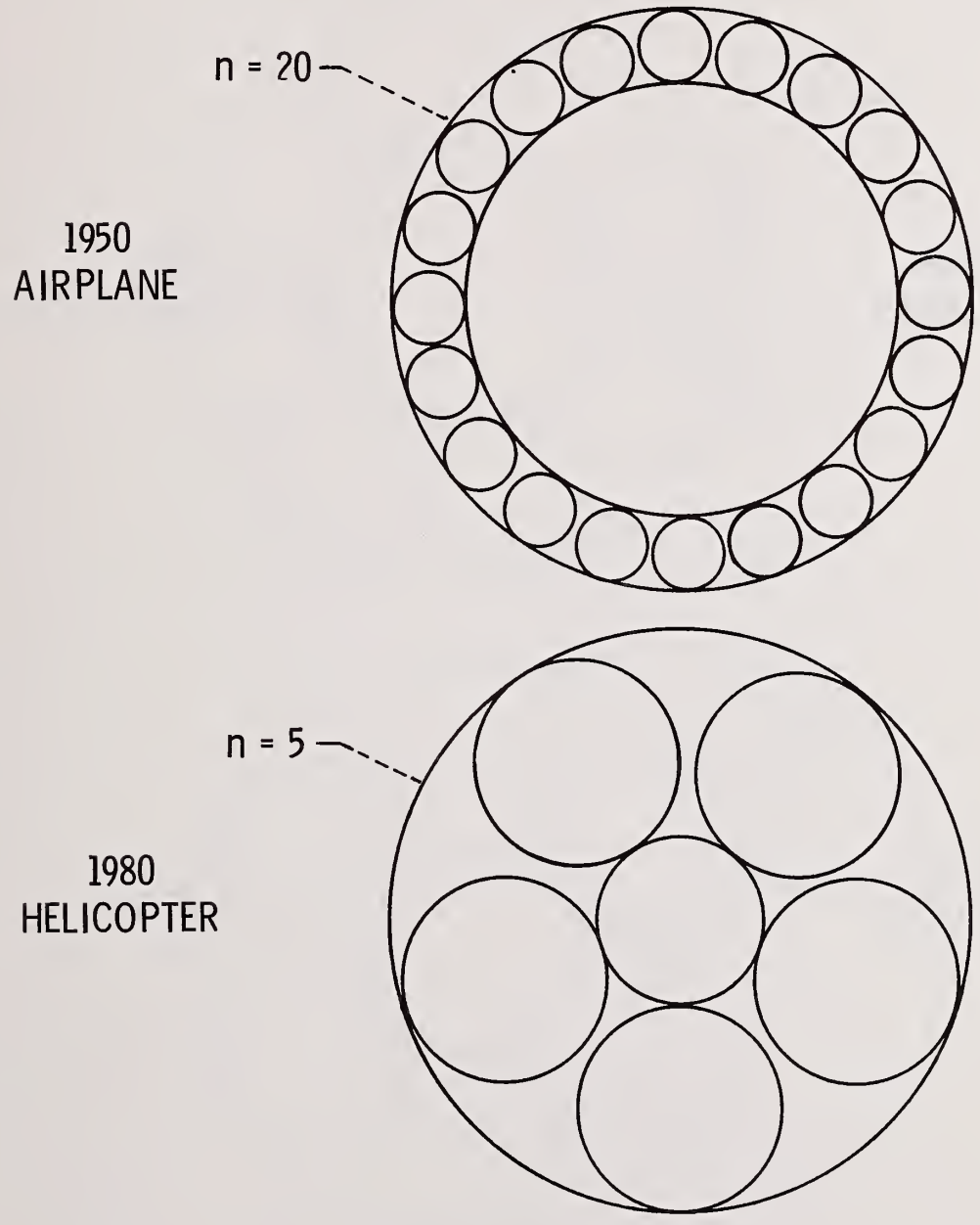


FIGURE 5.

INTERIM EPICYCLIC GEAR ARRANGEMENTS TURBOSHAFT ENGINES

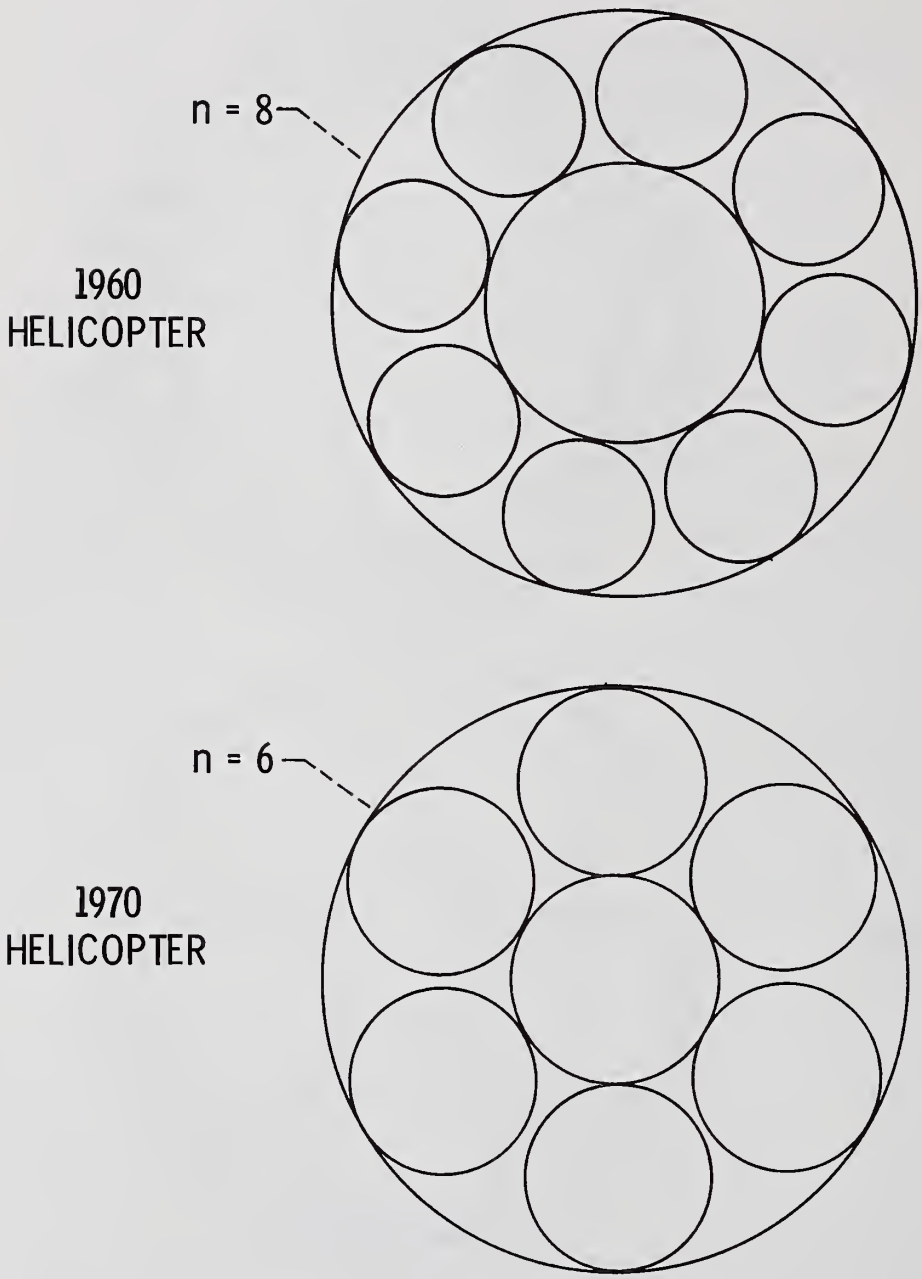
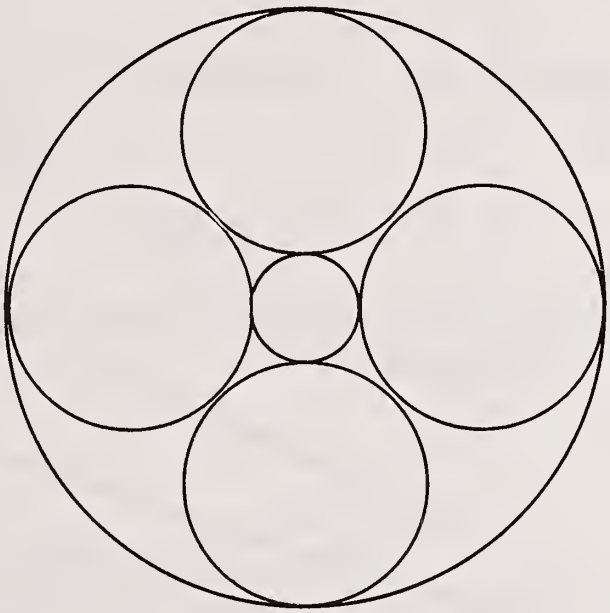


FIGURE 6.

EPICYCLIC GEAR ARRANGEMENTS
TURBOPROP ENGINES

1960
PROP-JET AIRPLANE



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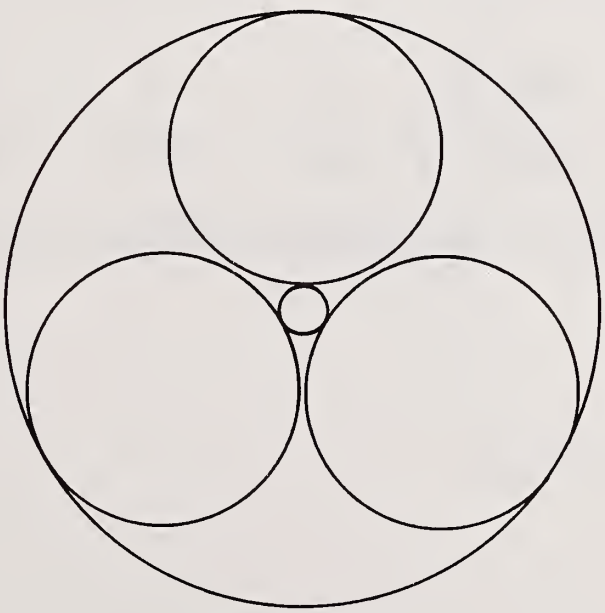


FIGURE 7.

EFFECT OF REDUCTION RATIO ON SUN GEAR LIFE EPICYCLIC GEAR SYSTEMS

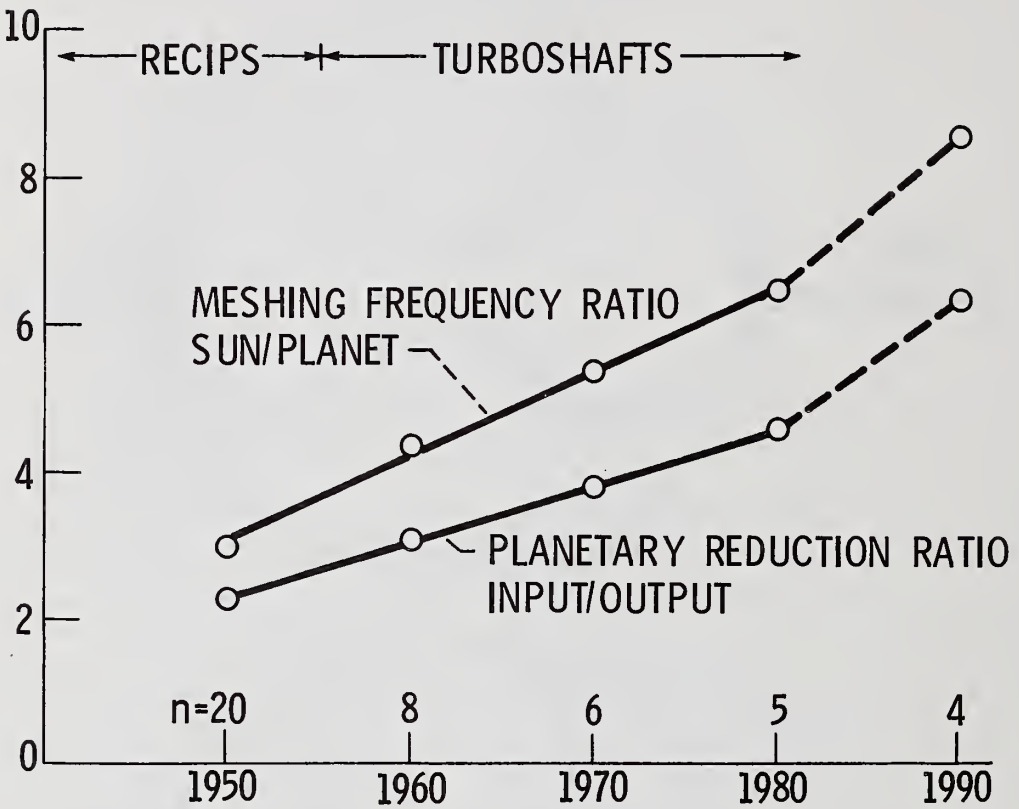
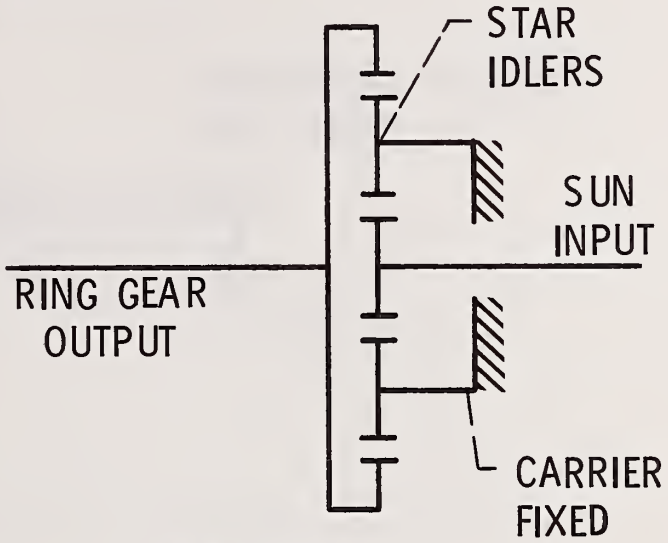


FIGURE 8.

TWO FAMILIES OF EPICYCLIC GEAR SYSTEMS

STAR ARRANGEMENT

REDUCTION: R/S
ROTATION, OUTPUT
VS. INPUT= OPPOSITE



PLANETARY ARRANGEMENT

REDUCTION = 1 + R/S
ROTATION, OUTPUT
VS. INPUT = SAME

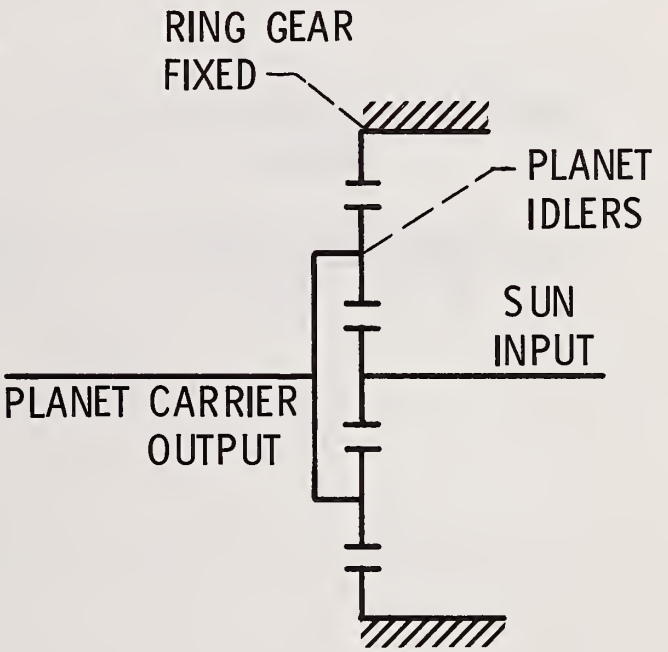
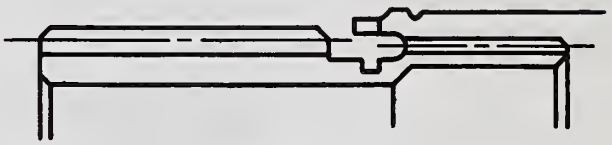


FIGURE 9.

DOUBLE-DUTY SUN GEAR

HELICOPTER

CURRENT: SHAFTGEAR
SINGLE DUTY



PROPOSED: REVERSIBLE GEAR
DOUBLE DUTY

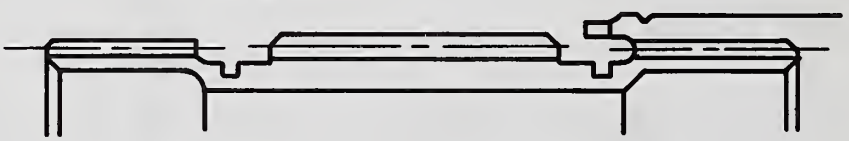
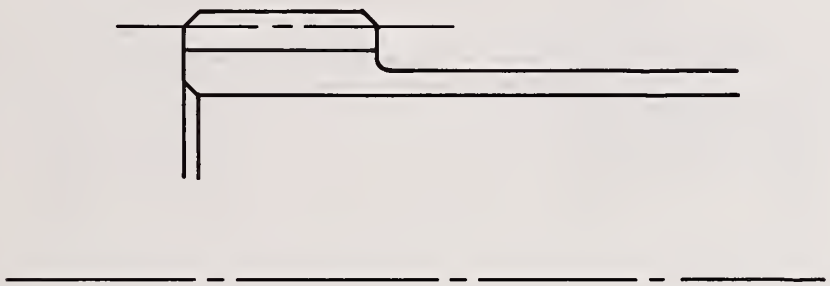


FIGURE 10.

DOUBLE-DUTY SUN GEAR

TURBOPROP

CURRENT: SHAFTGEAR
SINGLE DUTY



PROPOSED: REVERSIBLE GEAR
DOUBLE DUTY

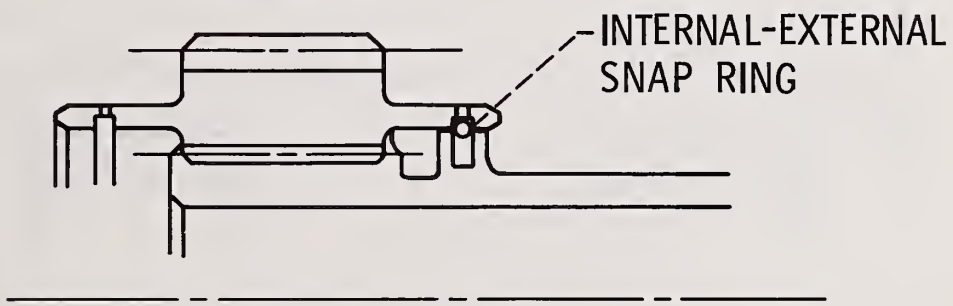
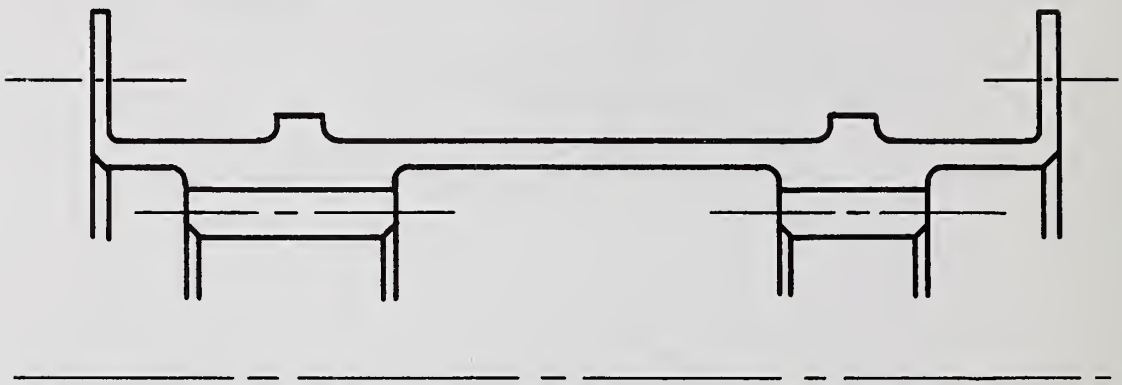


FIGURE 11.

DOUBLE-DUTY RING GEAR

HELICOPTER

CURRENT: ASYMMETRICAL GEAR
SINGLE DUTY



PROPOSED: REVERSIBLE GEAR
DOUBLE DUTY

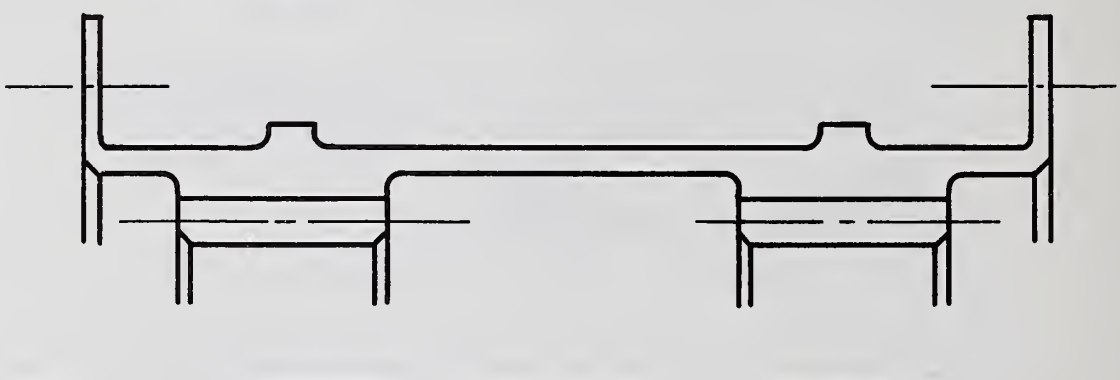


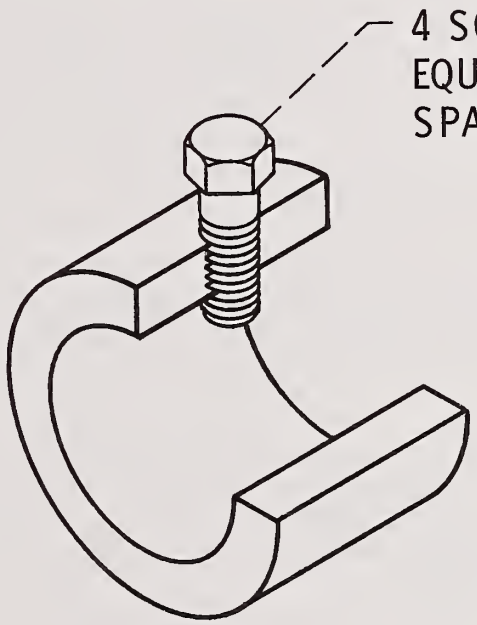
FIGURE 12.

ASSEMBLY/DISASSEMBLY TOOLS

INTERNAL-EXTERNAL SNAP RING
REVERSIBLE SUN GEAR

ASSEMBLY
TOOL

PISTON
RING
COMPRESSOR
(COMMERCIALLY
AVAILABLE)



DISASSEMBLY
TOOL

FIGURE 13.

EFFECT OF ANTIMONY THIOANTIMONATE IN GREASES ON ABRASIVE WEAR

J. P. King
Pennwalt Corporation
King of Prussia, PA 19406

Yayesh Asmerom
Pennwalt Corporation
King of Prussia, PA 19406

M. J. Devine
General Technology
Havertown, PA 19086

Abstract: There is a crucial need for effective lubricant additives that are capable of preventing damage that may occur due to contamination of lubricating systems by abrasive particles. This is an essential requirement for lubricants used in equipment and military vehicles that are operated in sandy environments. The effect of antimony thioantimonate ($SbSbS_4$) in three base greases—MIL-G-10924, MIL-G-24139, and MIL-G-81322—was investigated. The presence of $SbSbS_4$ in these greases provided considerable improvements in weld point, load wear index, and wear prevention properties with two different alloys. Moreover, impressive wear resistance properties were imparted by low concentrations of $SbSbS_4$ in these greases deliberately contaminated with hard abrasive particles. The combination of outstanding EP and antiwear characteristics and anti-abrasion properties of antimony thioantimonate makes this material an attractive candidate as a grease additive. Extensive field testing of greases containing this material is recommended.

Key words: Solid lubricant additive; antimony thioantimonate; abrasive wear; extreme pressure and antiwear properties; greases.

INTRODUCTION

Abrasive wear is well recognized as the primary cause of surface damage for military vehicles and equipment as well as industrial machinery.[1] This form of wear is encountered when foreign materials, e.g., sand, grit or other hard

particles become entrained in the lubricant. Sources of such hard particles include airborne contaminants entering the system during equipment assembly or repair, finely divided wear products from system components, fine debris resulting from oxidation or corrosion, and operation in sandy environments. Accordingly, a critical property of a lubricant material or additive is its ability to prevent or minimize component wear in the presence of hard abrasive particles.

Antimony thioantimonate ($SbSbS_4$), when incorporated into a number of selected greases as a solid additive at low concentration, imparts outstanding extreme pressure properties on both chrome tool and stainless steels.[2] An initial evaluation of $SbSbS_4$ in several military greases was conducted with the objective of selecting one or more of these greases to be formulated with $SbSbS_4$ for field evaluation involving sandy environment. To investigate additive response in the presence of abrasives, a grit material having precise composition and known particle size was incorporated into those greases with and without the presence of $SbSbS_4$. The extreme pressure and antiwear characteristics of these greases with and without $SbSbS_4$ and MoS_2 as additives were determined and compared.

PREPARATION OF ANTIMONY THIOANTIMONATE ($SbSbS_4$)

Antimony thioantimonate was prepared by the procedures as previously described.[2] A large supply of this material was synthesized in preparation for the coming field evaluation.

GREASES

Three fully formulated greases meeting the following military specifications were used as base materials:

MIL-G-10924 - Grease, Automotive and Artillery (GAA)
MIL-G-24139 - Grease, Multipurpose Quiet Service
MIL-G-81322 - Grease, Aircraft General Purpose Wide Temperature Range

GRIT MATERIAL

The grit material used in abrasive study was supplied by the A/C Division of General Motors Corporation, Flint, Michigan. It has an average particle size of 60-80 μ and the following composition:

SiO_2	68%
Fe_2O_3	5%
Al_2O_3	16%
CaO	3%
MgO	1%
Na_2O	5%
Ignition Loss	2-3%

TEST METHODS

Falex Machine

The abrasive wear study was carried out on a Falex machine using AISI-C-3135 steel pins (R_b87-91) and AISI-C-1137 V-blocks (R_c20-24). The testing speed, temperature, and load were 290 rpm, 77°F, and 100 lbs, respectively. The following procedures were employed.

1. Test specimens (pin and V-blocks) were cleaned with xylene followed by acetone and then air dried.

2. Test pin was inserted in pinholder.

3. Grooves of V-blocks were filled with grease sample and struck flush.

4. V-blocks were set in their sockets.

5. Jaw loading assembly was mounted on lever arms.

6. Jaw load was brought to a gauge load of 100 lbs (manual turning of ratchet wheel).

7. Drive motor was started and test run to 30 seconds, or to failure if prior to 30 seconds. Failure was indicated by rupture of pin or rapid torque increases above 40 in-lb and excessive noise.

8. Test pin was cleaned with xylene and acetone before making visual observation.

Four-Ball Testers

The extreme pressure and antiwear properties of the greases were determined on Shell Four-Ball EP and Wear Testers. These testers consist of steel spherical specimens sliding against each other. Weld points and load wear indices were determined in a series of runs (10 sec., 1800 rpm at 77°F) conducted at various loads, and scar diameters were measured after each run in accordance with ASTM-D-2596. Wear

prevention characteristics were determined by measuring scar diameters of test specimens after each run at specified rpm, load, temperature and duration (ASTM-D-2266). Two alloys—chrome tool steel AISI-C-52100 and stainless steel AISI-440C—were used.

RESULTS AND DISCUSSION

Abrasive Wear Study

Abrasive wear tests were conducted with the Falex machine for the three base greases (MIL-G-10924, MIL-G-24139, and MIL-G-81392), the three base greases with 5% MoS_2, the three base greases with 5% $SbSbS_4$, and same modified greases containing abrasive particles. The results for the abrasive wear resistance imparted by 5% concentration of $SbSbS_4$ in MIL-G-10924 and MIL-G-24139 greases are presented in Figure 1. It can be observed that severe wear and surface damage occur with either MIL-G-10924 or MIL-G-24139 (both containing 5% grit); however, $SbSbS_4$ virtually eliminates such wear and surface damage. Wear effects were also noted with MIL-G-81322 in the presence of abrasive particles, although the base grease is originally formulated to provide some degree of protection from surface damage in sliding contact. The presence of $SbSbS_4$ further improved the antiwear properties of this grease. The presence of MoS_2 in all the three base greases also provides some degree of surface protection; however, by visual observation the results are not as evident in all cases as those obtained with $SbSbS_4$.

Extreme Pressure and Antiwear Properties

As indicated earlier, all three base greases studied had been fully formulated at the source in order to meet the military specifications, i.e., they contained additives. Our primary interest was to improve abrasive wear resistance of these greases by incorporation of $SbSbS_4$; however, the extreme pressure and antiwear properties were also obtained in order to determine whether these performance properties were further improved by the presence of $SbSbS_4$.

We found that the weld points and load wear indices of MIL-G-10924 could be considerably improved by the presence of 1 to 5% $SbSbS_4$. At 5% concentration of MoS_2 no increase in weld point of this grease was observed; however, its load wear index was somewhat higher than the base grease. Indeed, the EP properties of the base grease containing 1% $SbSbS_4$ were found to be superior to those of the same base grease containing 5% MoS_2. The antiwear characteristics of

the base grease containing 1-5% $SbSbS_4$ showed slight improvement over its base grease. The experimental data are recorded in Table I. A graphical comparison of the data obtained on these greases is presented in Figure 2.

The weld point and load wear index of MIL-G-24139 containing 1% $SbSbS_4$ were significantly higher than those of the base grease. The weld point and load wear index of the base grease containing 5% MoS_2 were lower than that of the same base grease containing 1% $SbSbS_4$. The wear prevention characteristics of samples of the base grease containing 1% $SbSbS_4$ and 5% MoS_2, respectively, were comparable and were a dramatic improvement over the base grease on both chrome tool and stainless steels. The experimental data are recorded in Table II and a graphical presentation is shown in Figure 3.

Because of insufficient supply of MIL-G-81322 grease available to us at this time, load wear indices were not determined. The weld points of MIL-G-81322 containing 1 and 3% $SbSbS_4$ showed 25 and 100% improvements over the base grease, respectively. With 5% MoS_2 a weld point increase of 56% was observed. The base grease, as originally formulated, showed good wear prevention characteristics on chrome tool steel. No significant improvement of wear prevention characteristics on both chrome tool and stainless steels was achieved by incorporation of MoS_2 or $SbSbS_4$ into the base grease. The results are listed in Table III.

CONCLUSIONS

1. The abrasive wear resistance of both MIL-G-10924 and MIL-G-24139 greases was dramatically improved by incorporation of low concentrations of $SbSbS_4$.

2. The extreme pressure and antiwear properties of three base greases—MIL-G-10924, MIL-G-24139, and MIL-G-81322—were greatly enhanced by using $SbSbS_4$ as a solid additive. At a lower concentration this additive outperformed MoS_2 in all cases.

3. Antimony thioantimonate showed good response to both chrome tool steel AISI-C-52100 and stainless steel AISI-440C in all three base greases investigated.

4. If the presence of $SbSbS_4$ in these three base greases does not adversely affect other properties such as water washing out, rust prevention, drop point, etc. (investigation of some of these properties is planned), the use of $SbSbS_4$ as a solid additive in these greases

should be highly beneficial.

5. These results with $SbSbS_4$ as extreme pressure and anti-wear agent indicate potential for significant impact covering major improvements for lubricating greases, especially the current MIL-G-10924 (GAA) improvements being pursued by the U. S. Army Mobility Equipment Research and Development Command (DRDME-GL), Fort Belvoir, Va.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research. The guidance and encouragement provided by Commander Harold P. Martin is greatly appreciated.

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1. T. S. Eyre, "The Mechanism of Wear", Tribology International, 11 (2), 91-104 (1978).

2. J. P. King and Yayesh Asmerom, paper presented as an American Society of Lubrication Engineers Paper at the ASME/ASLE Lubrication Conference in San Francisco, Calif., Aug. 18-21, 1980 (ASLE Preprint No. 80-LC-7A2).

Table I. Weld Points, Load Wear Indices, and Wear Scar Diameters of MIL-G-10924 Grease Containing Additives

Grease Composition	Weld Point,[1] kg	LWI[1]	Wear Scar[2] Diameter, mm
MIL-G-10924 Grease (GAA)	160	29.3	0.62
" + 1% $SbSbS_4$	250	39.4	0.59
" + 5% $SbSbS_4$	315	56.7	0.59
" + 5% MoS_2	160	38.4	0.57

1. ASTM-D-2596 - AISI 52100 Steel
2. ASTM-D-2266 - 1200 rpm, 40 kg, 167°F for one hour on AISI 52100 steel

Table II. Weld Points, Load Wear Indices and Wear Scar Diameters of MIL-G-24139 Grease Containing Additives

Grease Composition	Chrome Tool Steel 52100			Stainless Steel 440-C
	Weld Point[1] kg	LWI[1]	Wear Scar Diameter[2] mm	Wear Scar Diameter[3] mm
MIL-G-24139 Grease (AMI)	126	14.1	2.17	3.48
" + 1% $SbSbS_4$[4]	315	38.1	0.58	2.18
" + 2% $SbSbS_4$	---	----	0.56	----
" + 1% MoS_2	---	----	0.64	2.55
" + 5% MoS_2	200	27.9	0.57	2.15

1. ASTM-D-2596
2. 40 kg, 77°F and 1800 rpm for 5 min.
3. 20 kg, 77°F and 1800 rpm for 5 min.
4. The presence of $SbSbS_4$ in MIL-G-24139 did not cause copper corrosion according to ASTM-D-130 (212°F for 1 h).

Table III. Weld Points and Wear Scar Diameter of MIL-G-81322 Grease Containing Additives

Grease Composition	Chrome Tool Steel 52100		Stainless Steel 440-C
	Weld Point[1] kg	Wear Scar Diameter[2] mm	Wear Scar Diameter[4] mm
MIL-G-81322 Grease (MOB)	160	0.41	2.31
" + 1% $SbSbS_4$	200	0.39	2.19
" + 3% $SbSbS_4$	315	0.56	1.88
" + 5% MoS_2	250	0.41	1.90

1. ASTM-D-2596
2. 40 kg, 77°F, and 1800 rpm for 5 min.
3. 20 kg, 77°F, and 1800 rpm for 5 min.

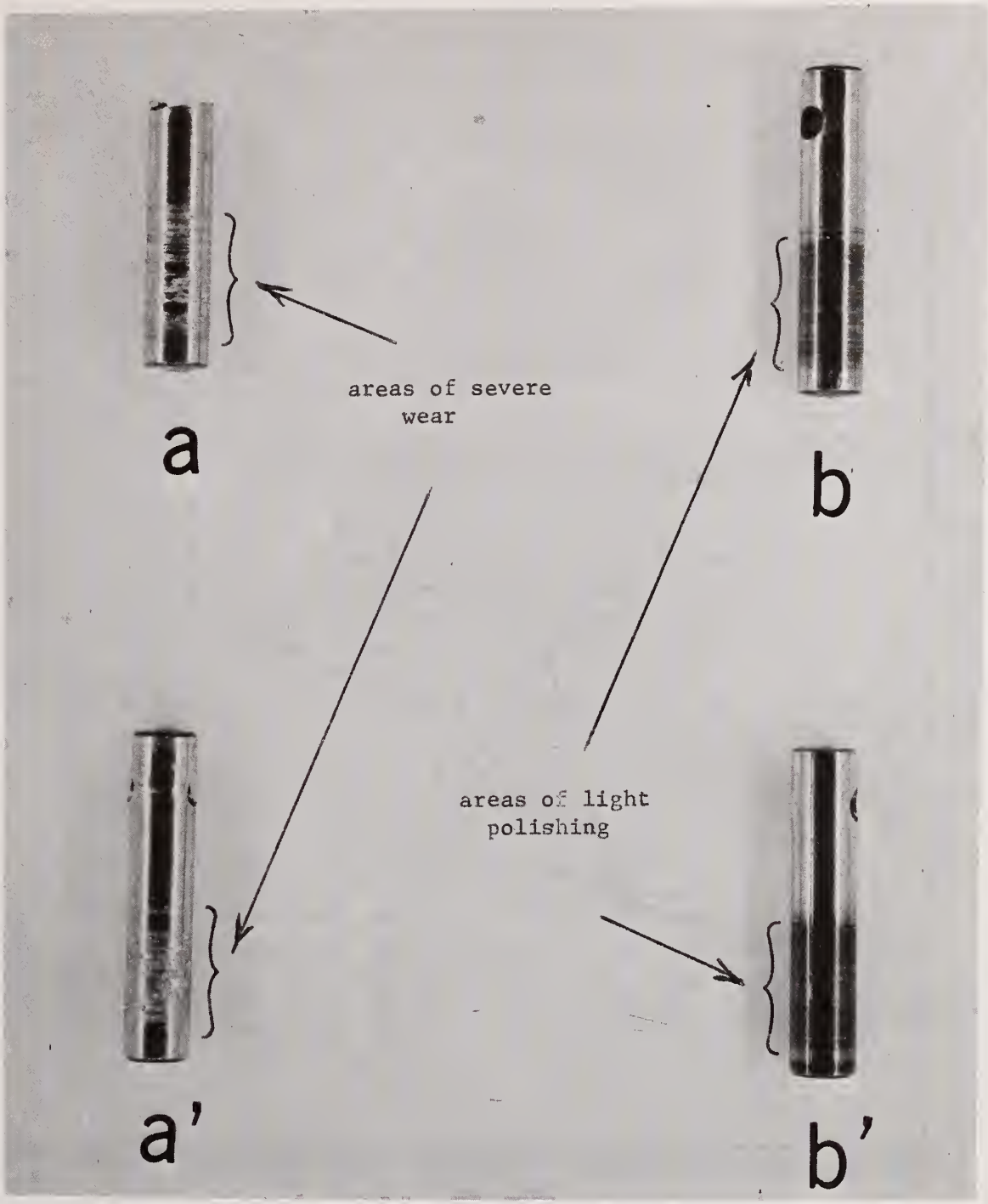

Figure 1. Effect of $SbSbS_4$ on Abrasive Wear

The outstanding wear resistance properties imparted by $SbSbS_4$ to greases containing grit particles (primarily SiO_2 60-80 μ) are illustrated by these Falex pins

a = grease MIL-G-24139 with 5% grit
b = " " " " and 5% $SbSbS_4$
a' = " MIL-G-10924 " "
b' = " " " " and 5% $SbSbS_4$

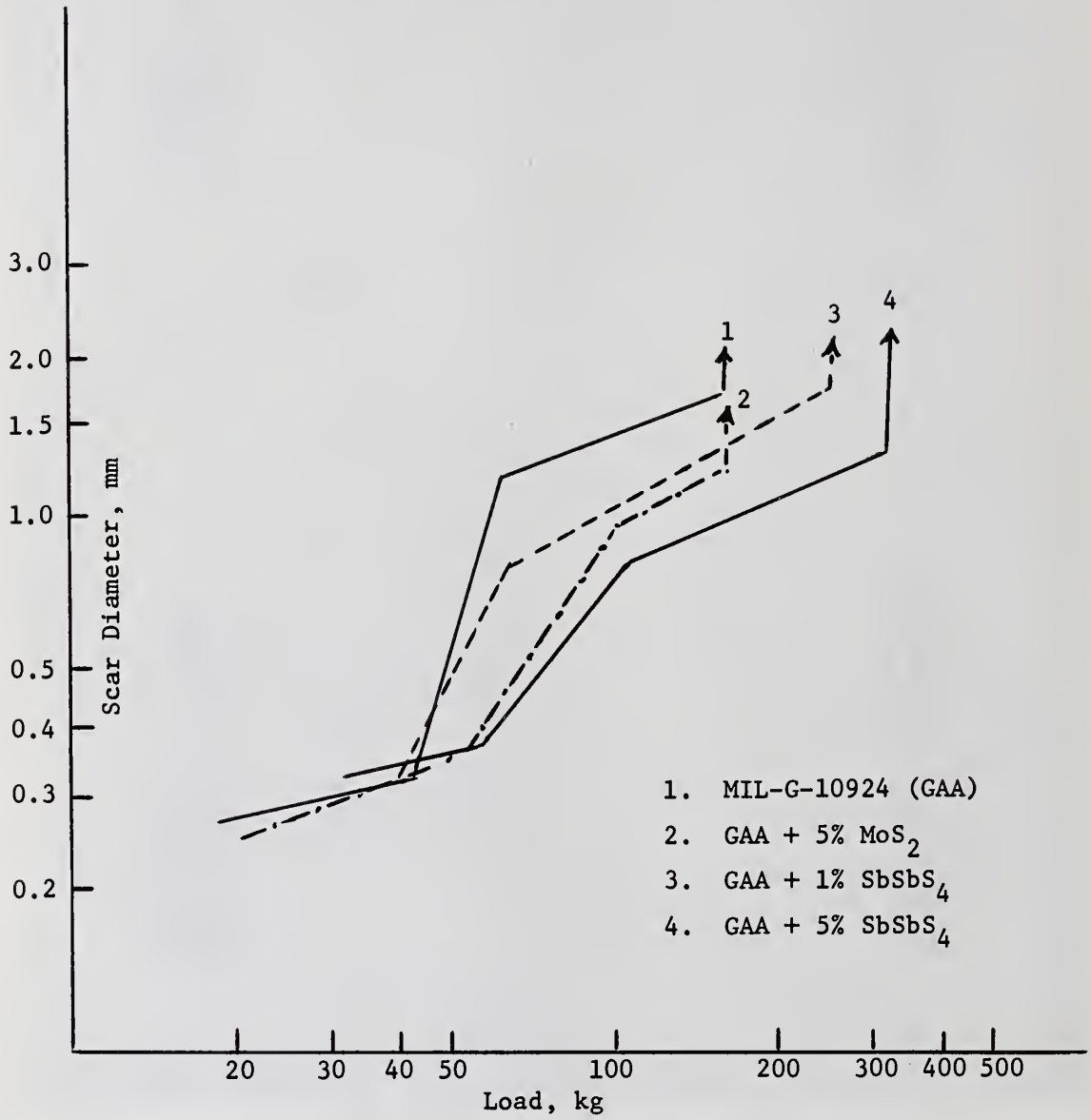

Figure 2. Wear Scar Diameter vs. Load; AISI-C-52100 Steel Balls; 25°C, 1800 rpm, 10s

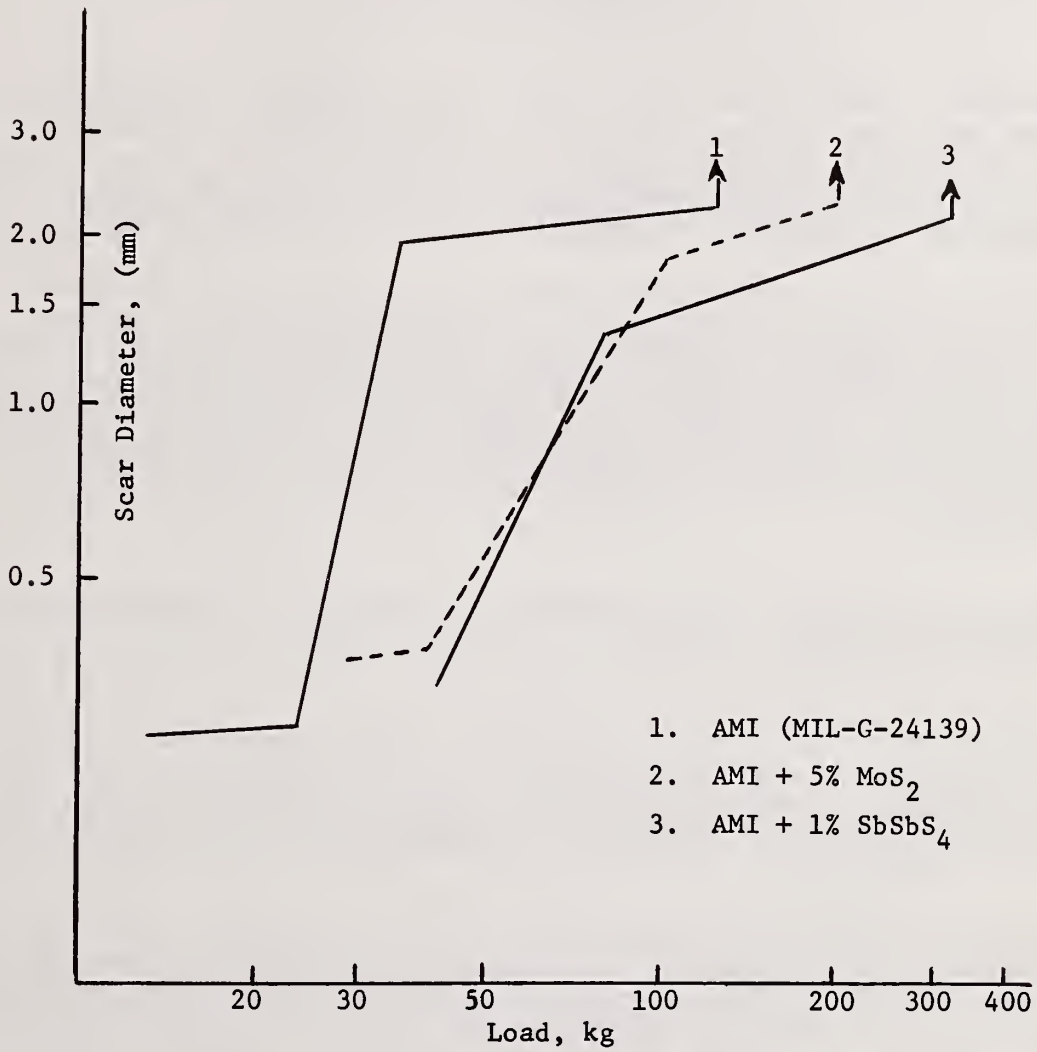

Figure 3. Wear Scar Diameter vs. Load; AISI-C-52100 Steel Balls; 25°C, 1800 rpm, 10s

SILICONE BRAKE FLUID: THE ANSWER TO REDUCED MAINTENANCE AND LONGER LIFE!

G. W. Holbrook
Associate Consultant
Dow Corning Corporation
2200 W. Salzburg Road
Midland, MI 48640

Abstract: One of the most costly maintenance items in a motor vehicle is the hydraulic braking system. Studies by the Department of Transportation indicate that on an average the hydraulic braking components are replaced at least twice during the life of a vehicle at a cost of $700 to $1000.

A thirteen-year development and testing program involving the U.S. Army, the Department of Transportation, and the silicone industry has resulted in the development of silicone-based brake fluids. Extensive testing has demonstrated the superior performance of these fluids which give promise of providing a hydraulic system which will need no maintenance for the life of the vehicle, exclusive of friction materials.

Key words: Long life; reduced maintenance; silicone brake fluid; U.S. Army.

A common goal of design engineers, maintenance engineers, and equipment users is to reduce maintenance while increasing durability and reliability. These goals are often incompatible without expensive and sometimes impractical engineering changes.

Although often not recognized, one of the most costly items in vehicle maintenance is the hydraulic braking system. Studies by the Department of Transportation indicate that on an average the master cylinder and wheel cylinders are replaced at least twice during the life of a vehicle.[1] In a fleet operation the average interval to the first master cylinder replacement is 15.8 months or 35,000 miles and 17.2 months or 38,900 miles to the first wheel cylinder replacement.[2]

Typical fleet practice is to perform a brake overhaul every 25,000 to 30,000 miles. Any hydraulic components which show

signs of leakage are replaced. At this second maintenance interval all components are automatically replaced, an operation estimated by one fleet manager to cost $350.00

Curiously, preventive maintenance programs sometimes obscure the real cost of brake system maintenance since emphasis is placed on reliability and elimination of unscheduled down time. Fleet managers take pride in the fact that they have no problems with hydraulic braking systems. Further discussion often reveals that the lack of operational problems are the result of a rigorous maintenance schedule. In one case, examination of a vehicle record card selected at random showed that nearly $1000 had been spent on maintenance of a seven-year-old vehicle!

In 1967 the Mobility Equipment Research and Development Command recognized the need to reduce maintenance and to increase reliability and life of braking systems on military vehicles.

Primary emphasis was placed on an improved brake fluid rather than hardware since major engineering changes in the braking system were considered impractical, and was brought about because of a need to use three brake fluids---an operational fluid for use in most theaters, an Arctic fluid for low temperature use, and a preservative fluid, installed whenever a vehicle was put into storage.

The logistics of maintaining three fluids in the supply system, the cost of repetitive fluid changes, and the general inadequacy of the operational fluid pointed clearly to the need for a single fluid, suitable for all three types of service.

An earlier unsuccessful evaluation of silicate esters and a successful program to develop a silicone fluid for use in rotary shock absorbers led the U.S. Army to initiate a joint development program with the silicone industry.[3]

The rationale for selecting a silicone-based brake fluid is brought into focus by a 1969 SAE publication entitled, "What the Brake Engineer Wants From Brake Fluid."[4]

In that paper the ideal fluid was described as:

---having a high boiling point, preferable over 400°F which is unaffected by any atmospheric condition.

---having the lowest possible viscosity at -40°F.

---being chemically inert, thermally stable, noncorrosive, and having no effect on paint.

---being compatible with every type of automotive brake fluid and brake hardware on the market.

These criteria demonstrate an uncanny fit with the properties of polydimethylsiloxanes, popularly referred to as silicones. These materials:

---have a high boiling point, typically 700°F in the viscosity ranges suitable for use in a braking system.

---do not attract moisture and thus will maintain their high boiling points.

---have the flattest viscosity temperature slope of any known polymeric material.

---possess outstanding thermal, chemical, and mechanical stability.

---are noncorrosive and do not attack paint.

An intensive development program over the next six years produced fluids which appeared to meet all criteria for a single, all weather fluid.

In March, 1973 a program was initiated by the Army to evaluate the performance of silicone brake fluids in military vehicles operating in a variety of climatic conditions.[5] The fluids were field tested for two years in direct comparison with conventional fluids at the Tropic Test Center (Panama Canal Zone), Yuma Proving Ground (Arizona), and the Arctic Test Center (Fort Greeley, Alaska).

The performance of the silicone fluids was reported to be "significantly better than that of conventional fluids."

The differences were especially striking in the Canal Zone where all conventional fluid-filled vehicles failed within one year because of corrosion, with water contents reaching 15.7%. In contrast, the silicone-filled systems were in excellent condition.

In Yuma, water contents reached a surprisingly high 8.4%, and caused severe corrosion, although all vehicles completed the two-year test. The condition of the silicone-filled braking systems was judged to be excellent.

1974 MUSTANG II
Pure Silicone System
123,650 miles...7yrs. Service

Figure 1.

In Alaska the test was conducted for only one year, primarily to document low temperature performance. Even after one year corrosion was noted in the polyglycol-filled vehicles.

As a result of these field test results a recommendation was made that all military vehicles be converted to silicone brake fluid.

The two-year field test, although impressive, did not truly demonstrate the increased life and reduced maintenance afforded by use of a silicone brake fluid.

Our test fleet has spanned ten years and includes over 300 vehicles from all domestic and most foreign manufacturers. Examination of components has documented that silicone brake fluids will provide maintenance-free operation, exclusive of friction materials, for the life of the vehicle.

One of our test cars was recently examined after seven years and 123,650 miles. Water content of the fluid was 200 parts per million. All components were found to be in new condition, with no evidence of bore wear, seal chipping or corrosion, as shown in Figure 1.

In 1977 the National Highway Traffic Safety Administration funded a contract to determine technical feasibility, expected economic impact and required lead times for a ruling which would require a long life warranty for hydraulic braking systems.

The contract report[6] concluded, "The survey task uncovered a body of testing data related to the use of silicone base brake fluids. --- Evidence appears to be sufficient to support serious consideration of their use in candidate long life braking systems."

Included in the recommendations were a number of engineering changes which would have increased vehicle costs by $12.50 per vehicle and which in the opinion of this author would be unnecessary. The incremental cost of OEM installation of silicone brake fluid is estimated to be $1.50 to $2.00 per vehicle.

Savings to the consumer, including the engineering changes recommended by the contractor were estimated to be $460,000,000 per year. Elimination of these engineering changes would result in savings of over $500,000,000 per year.

Legitimate questions have been raised concerning the risks

of substituting a fluid having substantially different chemical and physical properties into a braking system designed for polyglycol/polyglycol ether-based brake fluids.

These concerns included seal compatibility, the consequences of the inevitable mixing of the two fluids and the effect of water entry into a totally water intolerant fluid.

It has been demonstrated[7] that the base polydimethylsiloxanes, which shrink brake system elastomers, will function adequately in a braking system. However, government, military, industry, and SAE standards require controlled swell and a high degree of seal compatibility.

Elastomeric compositions used in braking systems are designed around the properties of conventional brake fluids. The task of formulating a silicone fluid to give controlled response with four dissimilar elastomers having widely different responses to plasticizers proved to be formidable, and was primarily responsible for the long developmental phase of the program.

As a result of the intense concern over seal compatibility, current silicone brake fluids are not only compatible with brake system elastomers but have been shown to be superior to conventional brake fluids.

In the most definitive study to date[8] "1200 immersion tests were carried out at temperatures ranging from 0°F to 248°F with fourteen different elastomers and five different brake fluids. It was found that silicone brake fluids performed as well as/or better than conventional fluids. Extended periods of exposure did not reveal any deficiencies."

Deficiencies were revealed in conventional fluids when tested outside the narrow ranges specified in current standards, as follows:

SBR - Shrinkage at ambient temperature.
EP - Shrinkage at 0°F.
Neoprene - Excessive swell at elevated temperatures.

Federal Motor Vehicle Safety Standard 116 and MIL B 46176 contain provisions designed to ensure compatibility of silicone fluids with conventional fluids. Although immiscible, the fluids are compatible and mixtures perform well in a braking system.

One vehicle in our test fleet operated for seven years and 93,000 miles on a mixture of 70% silicone and 30% conven-

tional fluid. Examination revealed a small amount of sludge in the polyglycol layer and some surface staining. However, there was no evidence of pitting, corrosion scale, or seal damage.

This vehicle was placed back in service using all the original components, this time using pure silicone brake fluid, and has now passed the ten-year mark and has accumulated 170,000 miles.

As a result of the extreme hygroscopicity of conventional fluids, water in a braking system has become an accepted fact of life to brake engineers. As a result, the concept of a totally water intolerant fluid was difficult to accept.

Extensive laboratory testing, plus well over four million miles accumulated by our test fleet, has demonstrated that water does not enter a silicone-filled system.

As manufactured, our silicone brake fluids typically contain 300 parts per million water. Humidification as specified in FMVSS 116 gives approximately 350 parts per million.

Ten vehicles were examined for water content after service use ranging from two to six years and mileage ranging from 6000 to 60,000. Water contents averaged 270 ppm.

The effect of direct addition to the master cylinder has also been addressed. Stroking data at high and low temperatures, submitted to the SAE Motor Vehicle Brake Fluid Subcommittee,[9] showed that water added to a silicone-filled system remained localized in the master cylinder and had little or no effect on performance; in a glycol-filled system the water migrated rapidly through the system, causing vapor lock at elevated temperatures and sluggish to inoperative brakes at lower temperatures.

Given the high levels of water typically present in a glycol filled system and the rapid migration of additional water through the system, these studies indicate that direct entry of water via the master cylinder would have a more deleterious effect with "water tolerant" polyglycols than with non-water tolerant silicones.

Summary

The seemingly incompatible goals of reducing or eliminating brake system maintenance while increasing durability, reliability and service life are clearly attainable and cost effective by use of silicone brake fluids.

This is best demonstrated by the title of MIL B 46176, issued in March, 1974:

"Brake Fluid, Silicone, Automotive, All Weather, Operational and Preservative."

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THE REQUIREMENT OF LUBRICATION SYSTEMS IN MAINTENANCE PROGRAMS AND NEW DEVELOPMENTS TO ENABLE MORE PRECISE CONTROL

C. Trainer
Interlube Systems, Ltd.
Plymouth, England

D. R. Rokos
Interlube, Inc.
Bensenville, Illinois 60106

A prime part of any maintenance program is the prevention of damage to moving parts, positive accurately controlled lubrication is essential to avoid costly breakdowns and to extend life of plant in its operational environment.

In simple terms effective lubrication is achieved when a film of lubricant is maintained between two surfaces in relative motion, this is generally termed as a Hydro-dynamic condition.

To maintain this condition lubrication systems are designed to supply quantities of lubricant either cyclically or continuously, the former more generally used enabling simplicity of machine design, this in turn creates problems of system design where outputs of lubricant injectors must be accurate and the timing of injection critical.

In recent developments it is possible to supply lubrication systems with inbuilt diagnostic controls which monitor all functional aspects including the actual passage of lubricant as it is discharged from the injector into the bearing. This latter development has been made using latest technology and removes maintenance engineers' anxiety and concern in being sure that lubricant has reached the moving parts and has not been dispensed via broken tail feed tubes or that a particular system injector has not operated.

The purpose of this paper is to examine the concept of lubrication in its use and to highlight developments which lead to more precise control and ensuring protection of costly moving parts which in turn leads to higher productivity.

FUNCTION OF LUBRICATION

To reduce friction or resistance to motion.

DEFINITION OF FRICTION

Friction is defined as 'that force which acts between two bodies at their surfaces of contact so as to resist their sliding upon each other'

TYPES OF FRICTION

1. Solid Friction:- two components in contact and relative motion. To sustain this motion great effort is required and heat generated.
2. Rolling Friction:- one component rolling on the other. Here at first glance there would appear to be no friction at all, other than the resistance of the atmosphere. However, we find that there is no perfect rolling action, some sliding or solid friction is always present.
3. Fluid Friction:- two components in relative motion prevented from making contact by a film of fluid lubricant. Here the friction depends on the fluid lubricants' ability to slide within itself. The effort required here to sustain movement and the heat generated is minimal. This is generally termed 'Hydro-dynamic' lubrication.

HYDRO-DYNAMIC LUBRICATION

Hydro-dynamic lubrication is achieved when a complex number of considerations which include type of oil, loads movement, amounts of lubricant to be supplied etc., are combined together to give the effect of a wedge of lubricant separating the asperities of solid bodies while in relative motion.

Let us consider a journal bearing through its cycle of rest and work:-

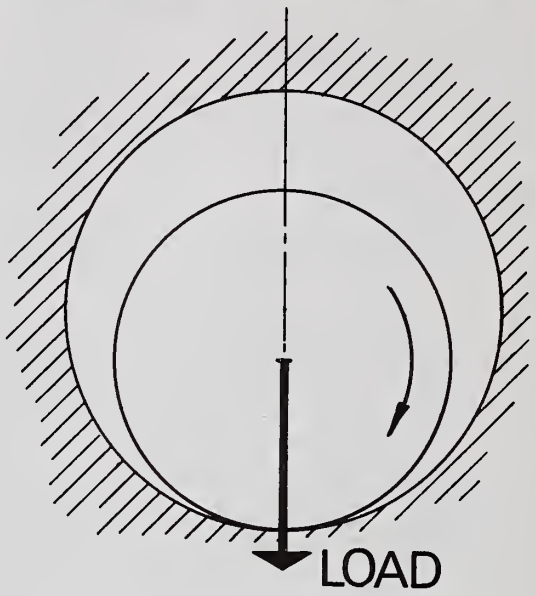
a) When the journal is at rest practically all the lubricant has been squeezed from the load area.

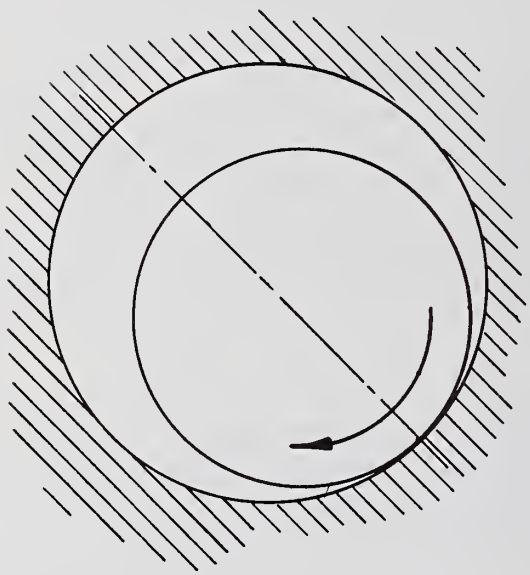
b) When rotation starts, with the clearance space filled with oil, the journal will tend to ride up the bearing surface and in so doing will entrain some lubricant which will pass between the journal and bearing surface. A wedge of oil is developed which will support the journal whilst it proceeds to rotate (see Diagram 1.).

This is the easiest example to show and understand. The principle remains the same for linear and oscillating bearings, with the wedge being assisted by lubricant 'ways' and the surface texture of the

FORMATION OF FULL FLUID FILM IN A JOURNAL BEARING

POSITION A
(at rest)





POSITION B
(start-up)

POSITION C
(normal speed)

oil film
supports
LOAD

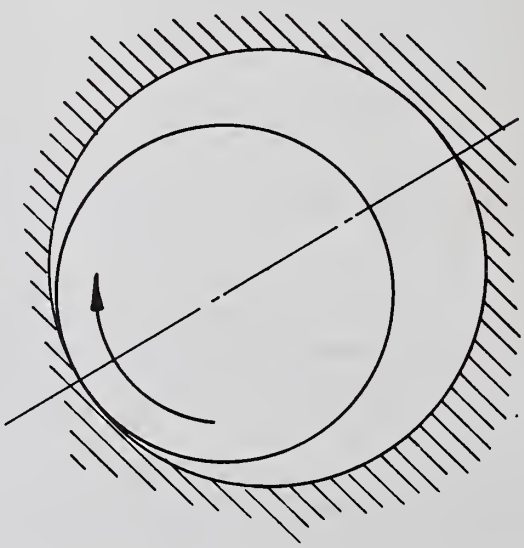


DIAGRAM 1.

moving bodies.

Hydro-dynamic lubrication is a most effective method of minimising wear and surface damage.

FLUID LUBRICANTS (OIL AND GREASE)

Oil offers advantages over grease since oil feeds more readily into the loaded contact area of a bearing. There is no known limit to the speed which can be attained with the correct amount of oil lubrication provided that the oil is delivered in correct quantities, at correct intervals, and is fluid enough to reach and support the moving parts.

Under certain conditions the plastic nature of a soap-thickened oil is prefered to the fluidity of a lubricating oil. Such a mixture of oil and soap constitutes a grease, the resultant lubricant is capable of forming a plastic lubricating film. Generally speaking greases are recommended where:-

a) mechanical design would result in excessive oil leakage.

b) in industries where excessive oil leakage might result in contamination of the finished product.

c) on slow moving parts which would have long intervals between re-lubrication.

DEFINITION OF OIL AND GREASE

1) Oil is a true 'Newtonian liquid' which means that the molecules of which the oil comprises slide over each other at a rate directly proportional to the force tending to make them slide.

2) Grease is defined by the American Society for testing and materials (ASTME designation D-288) as follows.
'A solid to semi-fluid product of dispersion of a thickening agent in a liquid lubricant. Other ingredients imparting special properties may be included.'

By definition grease is merely a lubricating oil plus a thickening agent.

Oil is therefore better suited to attaining efficient lubrication between moving bodies than grease.

OBJECTIVES OF PROGRAMMED LUBRICATION

The Four Rights:-

1) Right type in.
2) Right amount at.
3) Right place at.
4) Right time.

Resulting in:-

a) Safety of personnel.
b) Uninterupted production.
c) Extended machinery life.
d) Good housekeeping.
e) Lower operational costs.

CENTRALISED LUBRICATION SYSTEMS

Centralised lubrication systems fall into two main headings:-

1. Total loss systems - where lubricant is supplied in small quantities at pre-determined intervals, worked by the bearings and lost in the process.

2. Recirculating systems - where lubricant is supplied in flood quantities continuously to bearings, the lubricant that is not used is captured and returned to a sump or reservoir and re-cycled.

It is quite common to find both types of system on the same machine. Total loss supplying lubricant to slides, exposed bearings, or anywhere that design limitations make it impracticable to capture and re-cycle excess oil.

Recirculation systems in gear-boxes or enclosed housings where excess lubricant can be easily contained.

The two types of systems are subject material, each worthy of it's own paper. This paper will concern itself with the total loss system which is in daily use on virtually every moving mechanism.

TOTAL LOSS CENTRALISED LUBRICATION SYSTEMS

These systems can be divided into two main categories:-

1. Single line resistance systems.
2. Positive Displacement systems.

1. Single Line Resistance Systems

General description:- a prime mover forces a pre-determined volume of oil, under pressure, into the distribution system. Oil is apportioned to each bearing based upon its individual requirement by means of resistance fittings or fixed orifice flow control units.

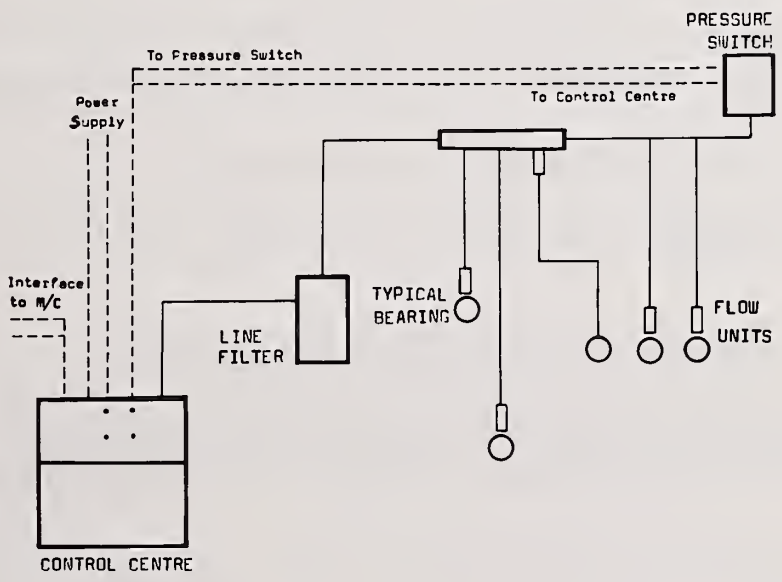
The interval between shots of lubricant is controlled in various ways, but the two most common are:-

i) build-up and discharge of a spring loaded accumulator.

ii) through an electronic timer switching a motorised gear pump on and off.

The electronic timer offers the most scope in setting parameters, and modern controls combine: a motorised gear pump in a reservoir, electronic timer with capacity to monitor low-level and pressure failure, incorporating inter-face facility to m/c panel, all housed in one unit.

A typical system layout is shown below:-



SYSTEM ANALYSIS

a) Suitable for oil only.

b) Manual or automatic.

c) Out-put pressure from prime mover 40 - 100 p.s.i. normally.

d) Monitoring available on basic system

i. broken line (i.e. pressure loss)
ii. filter blockage
iii. main line blockage
iv. low level

e) Installation relatively simple. Flow units compact and can be fitted direct into bearing housing

f) Low pressure system with small orifices. Flow units can be prone to blockage (not monitored by basic system).

g) Adding or subtracting lubrication points to a system can cause the system to go out of balance.

h) Blocked flow units should never be drilled-out to clear, as this changes the flow characteristic, but should be re-placed by a new unit.

i) In general, if a resistance system has been in service for sometime and a flow unit blocks-off, it is better to replace all flow units as their condition is usually related.

2. Positive Displacement Systems

These systems can be sub-divided yet again into:-

i) single line simple positive displacement injectors systems.

ii) single line series or progressive positive displacement systems.

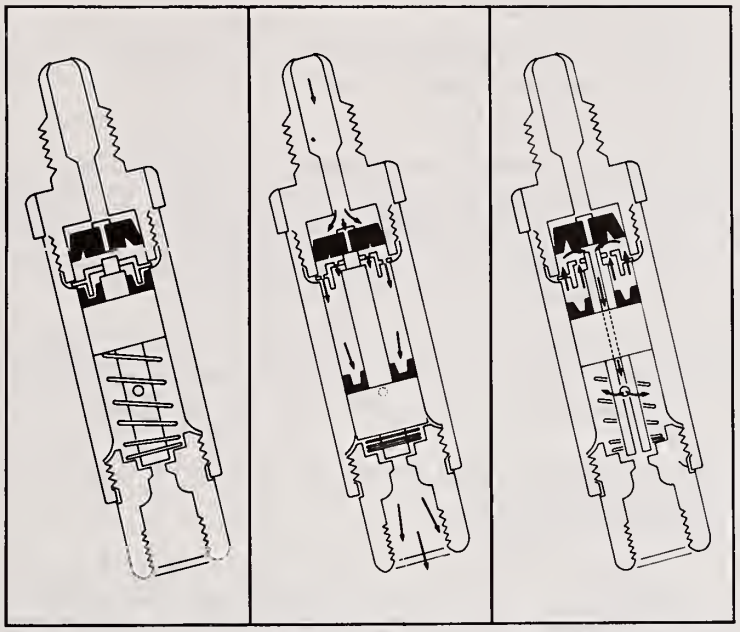
iii) dual line positive displacement systems.

These three variations represent the more common positive displacement systems in use today.

i) Single Line Simple Positive Displacement Injector

General description: the method of controlling the amount of lubricant supplied per cycle is through positive displacement injectors, which can be likened to single acting hydraulic piston

pumps. The best way to show how they work is in diagramatic form:-



a) At rest: prime-mover is at rest. No oil is being pushed around the system.

b) Delivery: prime-mover is switched on and oil is pushed into the main line, building up the pressure. At a pre-determined pressure the cup-seal on the inlet to the P.D.U. is pushed forward against the central tube, sealing the tube. As the pressure continues to rise the outer lip of the cup-seal collapses and allows lubricant to pass. The lubricant goes through the spider, supporting the central tube and onto the back face of the piston, pushing the piston forward displacing the lubricant in front of the piston, forcing it out of the injector, through a hole in the side of the tube and finally into the bearing. When the piston reaches its 'stop' no more lubricant is delivered to that bearing during this cycle. By varying the stroke of the piston the amount of lubricant delivered is increased or reduced.

When all the pistons in the injectors of a system have moved forward, the delivery of lubricant to that system for that cycle is complete, and although the prime-mover will still be operating its output being by-passed to the reservoir, no more lubricant is delivered to any of the bearings and eventually the prime-mover is switched off.

c) Transfer of lubricant: when the prime-mover is switched off, a pressure residual relief valve opens in the main line and reduces

the pressure back to atmospheric, the excess lubricant being returned to the reservoir.

This fall in main line pressure allows the cup-seal to expand back to its normal state, sealing-off the inlet of the injector and acting as a non-return valve.

The spring is now dominant and pushes the piston back, but the lubricant behind the piston cannot travel past the cup-seal. The cup-seal is thus lifted back off the central tube, allowing the lubricant to travel down the tube, transfering from the back of the piston to the front, as the piston moves.

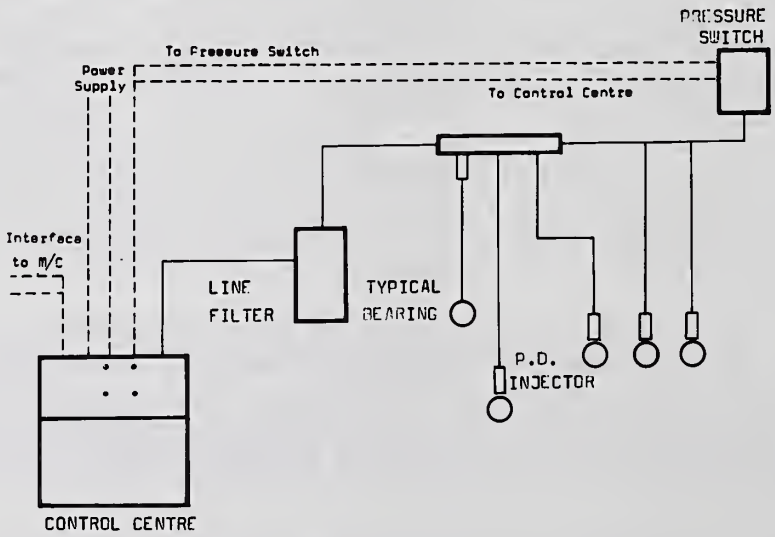
Note:- The piston is moving on a shaft so the displacement of lubricant on both sides of the piston is equal, making it impossible to draw lubricant back from the bearing.

d) At rest: as a) awaiting the start of the next cycle, when the prime-mover is switched on.

The principle outlined in a) to d) is common to this type of system although the technique may change from manufacturer to manufacturer.

The interval between cycles for this system is usually controlled by a motorised gear pump operated by a timer. As with the Resistance System the modern controller is of the combined type, i.e. motorised gear pump, electronic timer etc.

A typical system layout is shown below:-



SYSTEM ANALYSIS

a) suitable for oil or in some cases semi-fluid grease up to Index '0'.

b) manual or automatic.

c) out-put pressure from prime-mover normally around 300 p.s.i.

d) monitoring available on basic system

i) broken line anywhere in circuit.

ii) filter blockage.

iii) main line blockage.

iv) low level.

e) installation relatively simple. Positive displacement units are compact and can be fitted direct into bearing housing.

f) injector design makes a blockage or piston seizure a rarity, but should one occur the basic system does not monitor.

g) adding or subtracting lubrication points to a system is no problem.

h) positive displacement gives specific amounts of lubricant, delivered to bearings from .03cc per cycle upward. Amounts vary with manufacturer.

i) performance unaffected by back pressures.

j) failure of one lubrication point does not prevent others receiving the correct amount of lubricant.

k) a flexible system, widely used on medium to high production plant lubricated by oil or semi-fluid grease.

ii) Single Line Series or Progressive System

General description: the method of controlling the amount of lubricant supplied per cycle is a combination of prime-mover output and spool-valve movement.

The operation of the spool-valves is best observed in diagramatic form (see overleaf):-

fig. 1

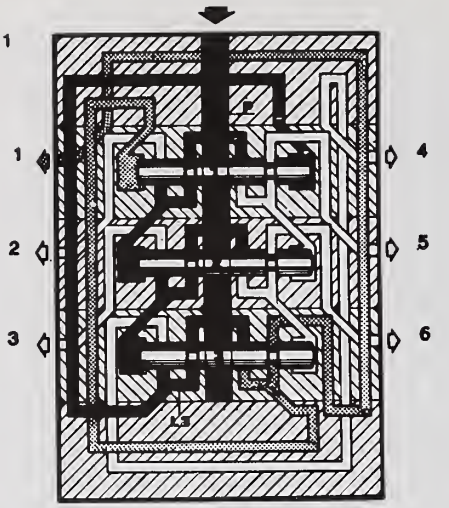


Fig. 1 shows the pressure path, i.e. dark shaded areas, as the first spool begins to move across.

The light shaded area shows the path of the lubricant out of exit point 1.

fig. 2

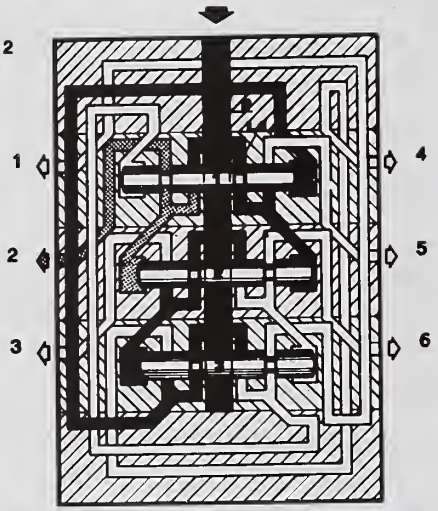


Fig. 2 shows the new pressure path, i.e. dark shaded areas when spool one has moved across and now spool two is forced to move. When spool two has crossed spool three will be pressured.

The light shaded area shows the exit path for point 2.

fig. 3

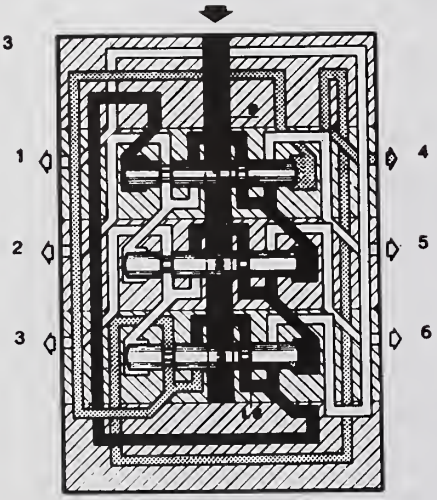


Fig. 3 shows the pressure path, i.e. dark shaded area when spool three has moved across. From this it can be seen that the pressure is now back on spool one but this time pushing the spool back and delivering lubricant out of exit 4 as indicated by light shaded area. Thus the cycle continues pushing spools two and three back and then starting all over again (see Fig.1)

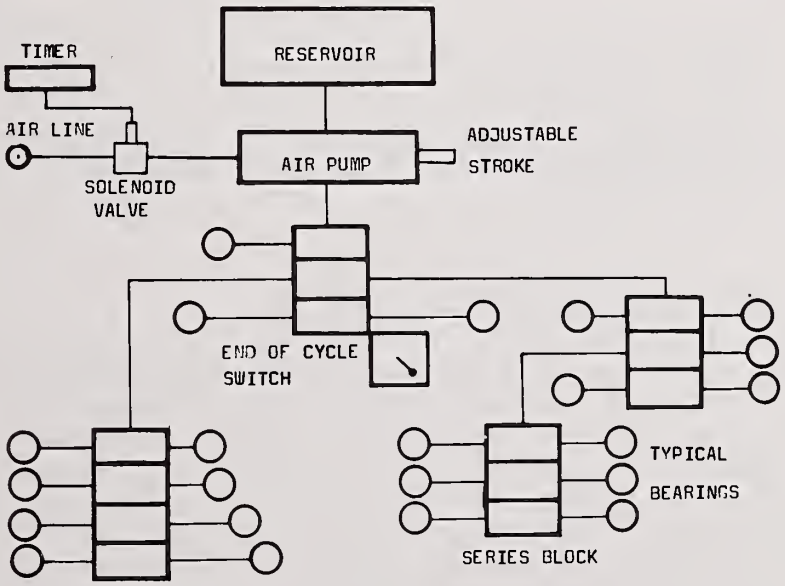
The three element block described (i.e. three spools) is the smallest block that can operate within the series principle. Larger element blocks (i.e. 4, 5, 6 etc.) operate in exactly the same way i.e. spool 1 then 2 then 3 etc., until the end one is reached and the whole block of spools starts to move back in sequence, spool 1, then 2, then 3 etc.

It may be noted at this point that if pressure is maintained on the inlet line the block will cycle over and over again. When the block has completed one cycle the prime-mover has to be switched off immediately or the block will begin to cycle again.

The interval between cycles for this system is usually controlled by a timer operating a single or double acting air or hydraulic piston pump with adjustable stroke. Motorised pumps can be used but are not as easily controlled.

The timer normally has capacity to monitor for lubricant level and end of cycle switching, incorporating an inter-face to the m/c giving shut-down facilities.

A typical layout is shown below:-



SYSTEM ANALYSIS

a) suitable for oil or grease up to Index 2.

b) manual or automatic.

c) output pressure from prime-mover up to 2000 p.s.i.

d) monitoring available on basic system.

   i) blockage anywhere in the circuit.

   ii) main line broken.

   iii) low level.

e) installation is complex. Blocks are bulky because the positive displacement spools are part of the block.

f) the spools are match-ground with bores, this means small particles of contaminent either in the lubricant or in the pipe cause the spools to bind. This is monitored by the basic system as a blockage. Broken pipes from block to block or block to bearing point cannot be monitored by basic system.

g) adding or subtracting points on a system is comparatively complex.

h) positive displacement gives specific amounts of lubricant delivered to bearings.

i) failure of one spool to deliver lubricant stops all other spools operating.

j) series systems are probably the only practical, cost effective means of applying measured amounts of grease to the lubrication points on small and medium machines. However, for oil systems the complexity of installation and lack of layout flexibility may outweigh any advantages over other Positive Displacement types.

iii) Dual Line Positive Displacement Systems

General description: the method of supplying lubricant is by movement of spool valves operating main pistons. Each spool and piston operates independent of the others in the system. This is achieved by connecting the P.D. units in parallel and supplying pressure to one side of the spools via the first main line, when all the main pistons have moved their full travel a reversor valve, operated by pressure in the main line, changes the out-put of the prime-mover to the second main line and relieves the pressure in the first main line, allowing the spools to be pushed back by the pressure in the second main line. The main pistons travel back. As the pressure builds up in the second main line the reversor operates again and the cycle begins again.

A typical valve arrangement is shown in diagram form below:-

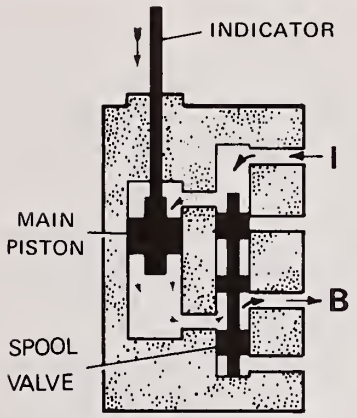


Fig. A) Lubricant from main line 1 pushes down the spool valve. Main piston is forced downwards delivering lubricant below piston through outlet 'B' to bearing.

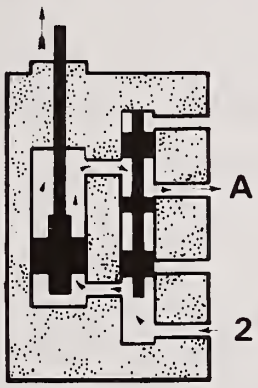
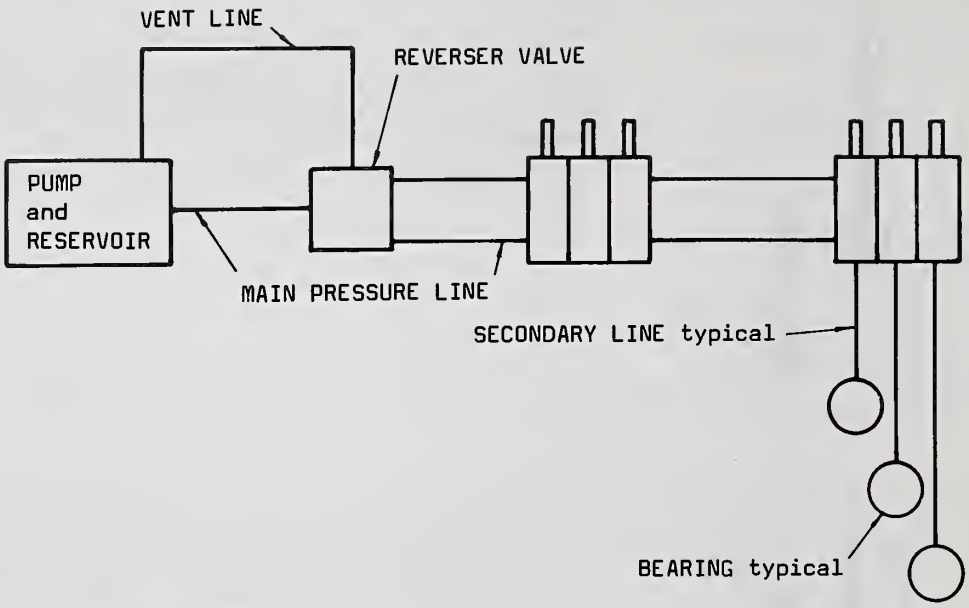


Fig. B) Main line 1 depressurised. Main line 2 pressurised lifting the spool valve. Lubricant above main piston is delivered through outlet 'A' to bearing.

The interval between cycles for this system is controlled by a timer switching a prime-mover. The main line reversor is usually automatic, and the timer switches off the prime-mover when the second line pressurises.

A typical system layout is shown overleaf:-



SYSTEM ANALYSIS

a) suitable for oil or grease.

b) manual or automatic.

c) out-put pressure from pump up to 5000 p.s.i.

d) monitoring available on basic system.

i) broken main line.

ii) main line blocked.

iii) low level.

e) installation complex. Two main lines instead of one and blocks are large.

f) system operates with spools again prone to seizure. Not monitored by basic system.

g) adding and subtracting points to a system no problem.

h) positive displacement gives specific amounts of lubricant delivered to bearing.

i) failure of one spool or main piston to operate does not prevent other points from being lubricated.

j) these systems are capable of applying grease to widely separated lubrication points on very large machines. Main application in steel industry and similar large equipment users.

LUBRICATION SYSTEM DIAGNOSTICS

All the systems we have looked at have their applications where they can be used to their best effect, but each system has disadvantages that cannot be overcome by layout or system design. These disadvantages are inherent faults that makes the system prone to failure, resulting in a starvation of lubricant to one or more bearing points.

As we have seen, some systems will monitor broken lines, others will monitor a blockage, but there is no basic system that will fully monitor the passage of oil to the bearing.

It is possible to add micro-switches, mechanically operated by plungers attached to individual P.D. units. It is possible to add pressure controlled micro-switches to each secondary line from the series block to the bearing, all in an effort to monitor that lubricant has entered the bearing, and all of these methods adds more complication, more moving parts to go wrong. In the end they are just not reliable.

The answer to the problem has been found using modern micro-electronic technology.

GENERAL DESCRIPTION

A transducer assembly has been designed for fitting into the bearing lubrication entry point. The transducer has no moving parts. It signals to a console that lubricant has flowed past it into the bearing during a lubrication cycle.

When the console receives a signal from one of the transducers in a system the console records that as a good point. At the end of a lubrication cycle any points monitored by the transducers that have not past lubricant are shown on a numbered read-out. The maintenance engineer reads the number of the lubrication point or points which has failed. That number corresponds to a reference on a lubrication circuit layout and the engineer is pointed quickly and accurately to the heart of the problem. Cutting maintenance and down-time to a minimal, but the main advantage is that the lubricant starvation has become obvious before it has become costly.

ANALYSIS

a) the system is called LUBESCAN.

b) it can be fitted to any of the lubrication systems previously discussed.

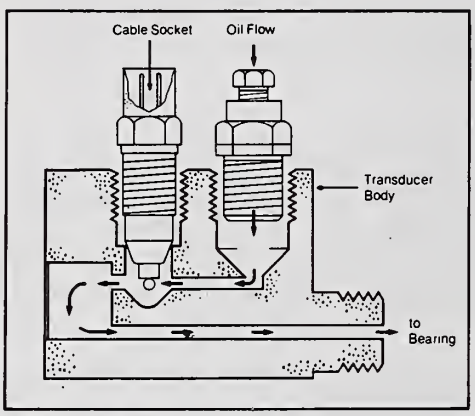
c) the system indicates that lubricant has passed into the bearing. Should lubricant not flow past a transducer for any reason, e.g. blockage, broken line, pump failure etc., then the system will

indicate the bearing or group of bearings not supplied with lubricant.

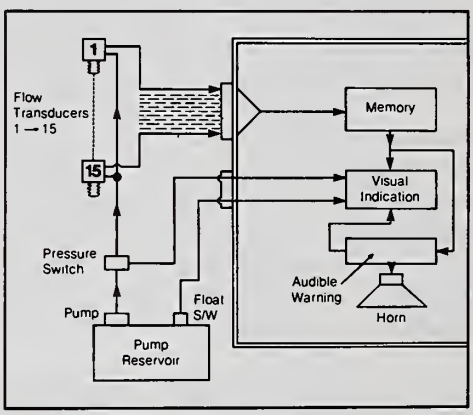
d) transducers do not have to be fitted to every lubrication point on a system. If required, only selected points may be monitored.

e) installation is simple and transducer assemblies are compact.

f) LUBESCAN can be retro-fitted to existing lubrication systems.



Transducer assembly



Lubescan - console

IN CONCLUSION

This short appreciation of industrial practices, the importance of correct lubrication and the comments on the most widely used systems will, we hope, give you a better understanding of this topic. Everyone knows moving parts require lubricating to keep them working properly, but how many people fully realise the improvements in overall performance which can be achieved by lubricating bearing areas correctly. This is an area where the preventitive maintenance engineer has a tremendous influence. An area of vital importance to plant engineers who are responsible for achieving agreed levels of production.

A major part of our activity is advising designers and users of machinery on the best way to lubricate their products or plant. This is a function we feel particularly well qualified to perform since we have available a wide range of lubrication equipment.

If you need any assistance on specific applications we shall be delighted to place our considerable technical resources at your disposal.

CONCEPTUAL PROPOSAL FOR SELF-LUBRICATING HIGH CARBON PISTON RING STEEL

Philip O. Badger
P. O. Box 54, Washburn Branch
Waterloo, Iowa 50706

Abstract: Molybdenum disulfide bonding to high carbon interstitial alloys utilized in the manufacture of piston rings is performed at an intermediate stage of the steel making process when voids existing between surface asperities are pronounced. Subsequent steps in the traditional steel making process impregnate the lubricant into the outer periphery of the cross-section by mechanical pressures. The alloy produced maintains the same physical properties such as yield strength and Rc hardness specified for piston ring stock but exhibits a sustaining self-lubricating characteristic of a bearing material.

Key words: Carbide precipitation; decarburization zones; implantment by mechanical inclusion; macro-molecular clustering; molybdenum disulphide imbedment.

It has been demonstrated in applicable dry solid lubrication investigations that molybdenum disulfide (MoS_2) has proven to be a versatile lubricant. Inherent basal cleavage intrinsically occurring within its atomic structure causes low lamellar shear strength. This property contributes to superior anti-friction and lubricity properties.

In prior work by the author in motor spring applications an inorganic bonded film containing MoS_2 was utilized to improve dynamic torque levels. This property has proved extremely useful in various MT fuze designs related to ordnance applications. Horological mechanisms of the classical design using escapement assemblies have in certain instances been operated 300% longer than those not using the coating before rewinding was required. These increased performance levels were a product of reduction in the kinetic coefficient of friction between the spring leaves during the unwinding process; from fully wound to fully extended. Also associated with these torque measurements, in the dynamic state especially, was a dramatic reduction in stick-slip phenomena historically associated with mainspring application technology.

Pursuant to this prior activity, a proprietary technique was developed for application of the bonded film containing MoS_2 to various substrates that has proven to be extremely cost effective. It is applied in a "coil to coil" operation at reasonably rapid rates. Adhesion properties of the film to the substrate has in all cases proved outstanding. The process also has demonstrated an ability to apply a uniform thickness to the surfaces of the substrate (as ultra thin as .00015" or as much as .0005" depending on thickness desired) irrespective of cross-sectional area or quantity. Due to this process, it is possible to apply a bonded film containing MoS_2 to metallic substrates of varying elemental composition at an intermediate stage of processing.

It should be noted that conventional application of bonded films of various dry film lubricants have traditionally been applied by spraying or dipping methods and subsequent drying and/or baking. These methods have precluded a procedure for applying lubricants at the intermediate stage of processing, as suggested herein. Most commercially utilized bonding agents react slowly. The bonding agent used in the "coil to coil" procedure reacts very rapidly permitting a recoiling operation immediately after the solvent is flash evaporated.

Certain piston ring materials now being used in internal combustion engines are fabricated from alloy variations of high carbon steel. Some of these materials are furnished to piston ring manufacturers by steel suppliers in flat strip cross-sections; for example, .024" x .105". These materials are produced by a combination of cold working and tempering in order to achieve suitable strength and hardness parameters for application in the piston assembly.

In the process, breakdown sizes of larger diameters than the finished size in terms of cross-sectional areas are produced from larger diameter hot rolled stock. To relieve the stock from dislocation of its crystal lattice at these various breakdown sizes an annealing operation is done at the metals "recrystallization temperature" which relieves residual stress and restores the alloy to its original state. This condition then permits further cold working. A by-product of the annealing process not frequently discussed is a phenomenon called "carbide precipitation". The formation of the precipitates in interstitial alloys generally speaking is a process best described as macro-molecular clustering which causes asperities in the surface finish. At the termination of the annealing cycle cooling period the voids caused by precipitation are more pro-

nounced than they are when the finished surface is reduced to final size. Also occurring during the annealing process is the discharge of carbon monoxide (CO) and carbon dioxide (CO_2) creating decarburization zones. Typically these zones in highly interstitial alloys such as the one being discussed is between .001" and .002". To control this phenomenon, many producers have started using vacuum melting procedures and other control measures during the annealing cycle. (Dr. John Smith (1))

The proposal being made herewith entails incorporating an intermediate process subsequent to annealing, and before reducing to final size and tempering. This process would lubricate the substrate in a "coil to coil" operation with a solid lubricant as discussed previously. At this stage of processing, the lubricant would then be imbedded in the micro-voids or surface imperfections that result from carbide precipitation and decarburization. It has shown that by sandblasting or phosphating various alloys preparatory to being treated with MoS_2 bearing lubricants, "micro reservoirs" form in their surfaces that are used for storage areas for the lubricant and "suggest that this is essentially what is occurring in the case of optimum surface finish." (M. J. Devine et al (2))

It has been shown that the formation of the transferred film appears to be primarily a mechanical process with three distinct processes: (a) direct imbedding of the solid into a softer surface, (b) deposition of the solid into surface depressions generated in the substrate during sliding by the abrasive action of the solid itself, (c) deposition of the solid into the surface depressions characteristic of the original surface finish and surface hardness of the substrate. (J. K. Lancaster (3,4))

Since the surface hardness of the steel substrate will be less after annealing than it will after final drawing and tempering, the MoS_2 can be applied most effectively at this time. Then during final drawing, the extreme pressures developed will imbed the MoS_2 into the surface of the steel. Also, the anisotropic properties of MoS_2 permit the material to partially penetrate the bottom of the reservoir voids more so than would be possible when applying the lubricant to a substrate with a high superficial hardness.

When the resulting substrate is in a "prelubricated condition" and is then reduced 60-70% in cross-sectional area, plastic deformation or dislocation occurs in the grain structure of the alloy. An essentially spheroidal grain structure characteristic of the annealed condition of the

substrate will be changed to a hyper-extended or elongated grain structure. MoS_2 molecules existent on the surface of the steel will ease the frictional pressures when the material passes through the wire drawing dies and will shear along the basal plane. Inherent to this process, however, would be the implantation by mechanical inclusion of the solid lubricant into the surface depressions (surface imperfections) characteristic of the post-treated surface of the substrate.

It is noteworthy to consider that the alloy is essentially unchanged from an elemental composition point of view. As a result, work hardening properties, hardness characteristics and yield strengths are the same. However, due to trace amounts of MoS_2 implanted and included on the outer periphery of the cross-section, improved bearing properties favorable for reduced friction and increased wear performance would exist.

The alloy produced would have desirable "bearing properties" but the essential properties necessary for piston ring applications would be uncompromised.

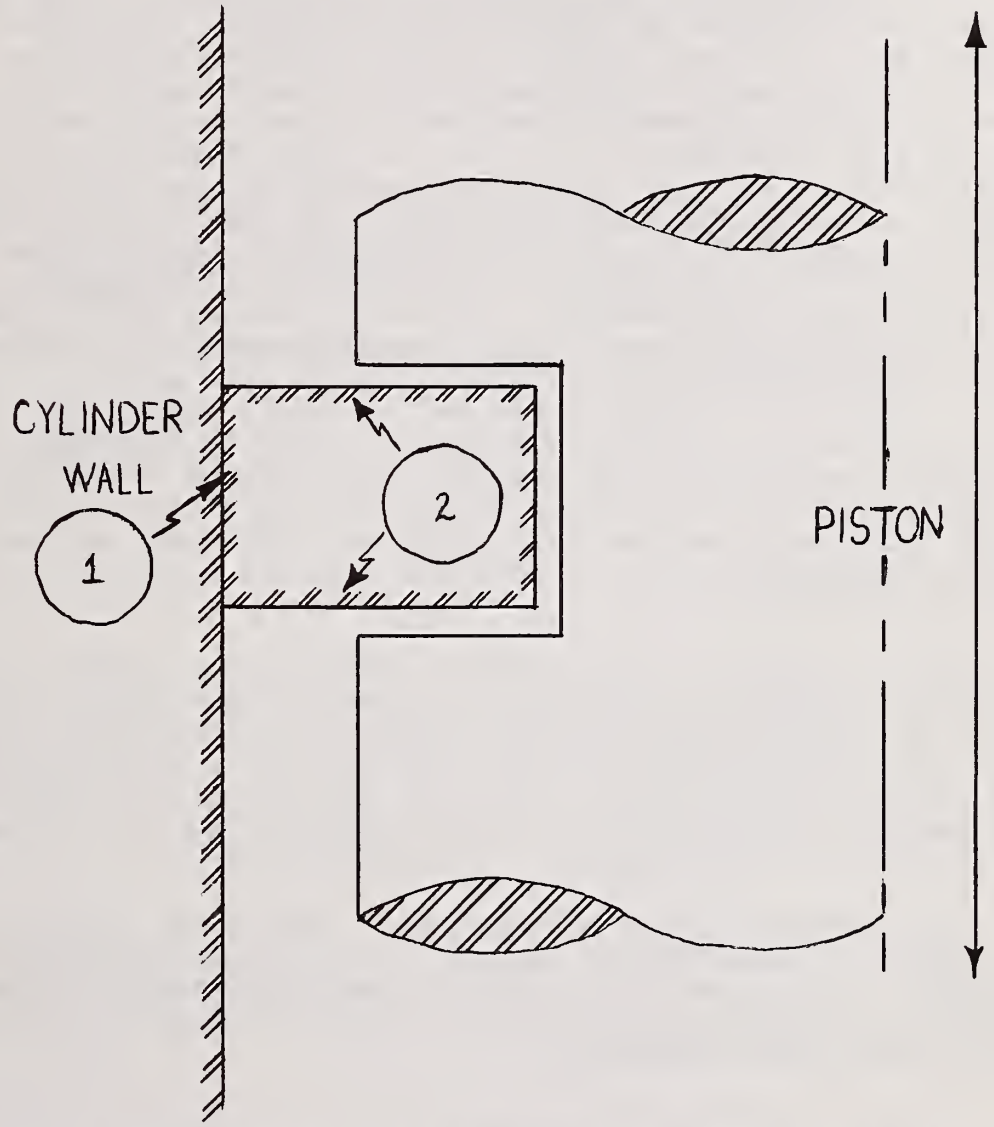
Radial wear characteristics of piston rings have been compensated for in some mechanical designs by utilizing a material with "spring" properties, that exert an outward force on the cylinder wall due to inherent elasticity of the material. This design acknowledges the fact that wear will take place. From a cross-sectional standpoint, the lubricant would not only be present on the wear surface which is the smallest of the keystone surfaces employed, but also homogeneously present on the surface fit into the piston grooves which is the larger surface. When exhaustion of the lubricant occurs in the outer periphery of the ring, it would be replaced by that present in the adjoining micro-radial cross-section. Plate (1) illustrates the cross-sectional lubricant implantment in the ring and shows how supplemental lubricity can be anticipated.

This alloy would then be able, for the life of the ring, to supplement normal lubrication between the piston ring and cylinder wall that is mainly hydrodynamic. Piston rings treated in this manner would be able to perform more efficiently some of the required functions demanded from traditional bearing materials. They are as follows:

1. Withstand high loads at appropriate operating temperatures.
2. Operate for short periods of time with only boundary lubrication.

Mechanical drawing of this plate are efforts of Julia Fish, Senior, Mayo High School, Rochester, Minnesota.

PLATE ONE
PISTON ASSEMBLY



When the implanted MoS_2 is exhausted on surface one (1) it will be replaced by implanted MoS_2 on surfaces two (2) nearest the cylinder wall.

3. Redistribute local high loads.
4. Improve wear characteristics of the mating surface due to inherent anti-friction properties.

Practical benefits such an alloy would yield are beyond the scope of this proposal. However, the alloy would tend to reduce wear of the cylinder wall in an internal combustion engine at top and bottom dead center of the piston assembly, in the areas of the cylinder wall where oil films are unable to accumulate in sufficient film thickness due to the reciprocating action of the piston assembly. Also, the pistons and rings have zero velocity at dead centers so that the hydrodynamic requirement of relative velocity between opposing surfaces is not met and lubrication must rely upon the squeeze-film effect in these areas. (E. R. Braithwaite et al (5)) Parallel studies by numerous others confirm this finding since cylinder wall wear in life cycle testing is greatest in the precise areas opposite these two piston operating positions. The proposed alloy would provide beneficial supplemental lubricity because of the implanted solid lubricant. Thus increased wear performance is reasonably anticipated.

A residual benefit worth considering would be the reduction of initial scoring of the cylinder wall during break-in by the mating ring. This would be due to a smoother surface on the ring and also due to initial dry lubrication previously determined to be a positive benefit to general engine performance.

A project to produce this alloy to determine beneficial effects with respect to friction and wear is proposed. Engineering disciplines including these which consider the metallurgical properties of the alloy need to be employed in order to establish the extent to which the alloy will make positive improvements in the operation of the piston and cylinder of the internal combustion engine.

The exact nature of the research will depend on the type and amount of information desired by the funding agency. Pursuant to this goal officials at the Department of Transportation employed by The Bureau of Basic Automotive Research have been contacted.

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Engineering, Iowa State University of Science and Technology, Ames, Iowa in the preparation of this paper.

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THERMAL DEPOSITION SYSTEMS FOR IMPROVED MAINTENANCE

Vincent J. Lanza
Government Marketing Manager
METCO, Inc.
Westbury, New York 11590

Abstract: The military has a continuing need to improve the service life of its equipment. The Navy with its ships and shipboard equipment exposed to marine environment, as well as erosion and wear, has an everlasting requirement to keep its equipment in readiness. The Navy builds its ships to have a thirty (30) to forty (40) year service life. The latest designs of these ships are the DD963 Sprunce Class Destroyer and the Frigate Class Ships. This paper will attempt to describe the applications implemented aboard ships of this class dealing with corrosion, erosion and wear. We will also attempt to describe the equipment, along with the application, and their respective economical advantages. The Navy being one of the forerunners using this process, is by no means the only one. The Army has implemented applications in its new gas turbine used in the XM1 Tank. In attempting to stress the use of the flame spray process, guidance is recommended. The new industry and program to be discussed in this paper will be the diesel rebuilt market and the applications already implemented by the original equipment manufacturer.

Key words: Thermal deposition systems; plasma coatings; aluminum non-skid coating; corrosion control; thermospray process; erosion; wear; flame spray process.

The function of the METCO Government Marketing Department is to develop the use of the thermal spraying process within the military and to act as liaison between military agencies and the O.E.M. (Original Equipment Manufacturers). Agencies are encouraged to consult with each other directly based on technical results and facts.

The programs and applications in process, to date, include the gas turbine engine for the XM1 Tank. This engine is being manufactured by Avco Lycoming and has seventeen (17) separate applications designed into it. These applications, produced by computerized equipment designed and built by METCO, provide protection from wear, erosion and corrosion and are thus increasing engine life and efficiency.

The Army is using the process in both R & D facilities such as ARRADCOM, Watertown Arsenal and Fort Monmouth, as well as at Depot level. The depots are reviewing the process to extend the life of equipment already in line such as M60 gun mounts, road arms and many others.

The Air Force, on the other hand, is also a very strong proponent of the process. The ALC, Kelly AFB, Tinker AFB, Wright-Patterson AFB, Hill AFB as well as Warner Robins, are all very active users. The jet engines turned out by these ALC's each have thermospray or plasma coatings applied per specifications developed by the manufacturer. However, military personnel with METCO assistance have developed applications beyond the scope of the O.E.M. with great success. These approved applications have resulted in cost savings to the Air Force in both funds and engine turn around time.

The Navy has used the process at the NARF's (Naval Air Rework Facilities) in the same manner as the Air Force. They have extended the process use to ships and shipboard applications. COMNAVSURFPAC has made it Navy policy to use the aluminum wire thermospray process on all valves to eliminate corrosion. This process is being extended to all applications above the waterline. This program is being implemented at Ingalls Shipyard on the Sprunce Class Destroyers and the Frigate Class.

The Navy, with METCO, developed an aluminum arc sprayed non-skid coating that was first used on the USS Truett with great success. Since then, it was applied to several other ships including the USS Hewitt and USS Fox, with equal success. The aluminum non-skid coating has outlasted the conventional non-skid coating and provides corrosion protection as well.

The coating, when applied to the helo deck, has eliminated a serious problem with the tie downs. These items, generally made of stainless steel mounted to a 6061T6 helo deck, caused exfoliation and a costly repair. The coating has eliminated this problem on all decks sprayed at this time.

The Navy is extending the process to cover machine repair components and has issued a series of specifications to cover the aforementioned applications. The most recent is Mil-Std-1687, which covers procedure operator certification, as well as materials. Others are as listed:

1) Corrosion Control for Shipboard Launch and Recovery Systems (NAVSEA and N.A.E.C.)
2) Navy Policy - Flame Spray Valves (COMNAVSURFPAC)
3) Job Performance Aid for Applying Wire Sprayed Aluminum
4) DD963 Corrosion Control Manual
5) Equipment Specification Available:
   Mil-M-3800, Wire Systems
   Mil-P-80141, ThermoSpray Systems
   Mil-P-80109, Plasma Spray Systems
6) Materials Specification Available:
   Mil-W-6712, Wire
   Mil-P-83348, Powders
   Mil-Std-1687, Process and Materials

The propulsion unit used in the Navy's latest destroyers is the LM2500. This unit is manufactured by General Electric and contains eighty-one (81) applications in the compressor section at 1100 degrees F and seventy-five (75) applications in the turbine section. METCO has worked very closely with General Electric to provide the proper material and process for each of these applications.

The development of a new series of one-step materials has given METCO the opportunity to penetrate the diesel engine market. METCO has contacted all of the major diesel engine manufacturers to demonstrate the process in major problem areas. Areas being reviewed are the engine blocks, turbo chargers, water pump engine components and automatic transmissions. It was demonstrated that by applying METCO 444 one-step stainless steel to the saddle and thrust faces of a diesel engine block, that a $3,000 block can be restored at a cost of $200.00. METCO has documented all of its applications on diesel engines and is providing this documentation to the Navy and other agencies to repair or authorize the repair of its diesel engines.

It was estimated, based on the first quarter of FY'81, that the Government will spend $930 million annually on rebuilt or replacement parts. Out of this, $190 million worth of used parts are suitable for repair by the thermospray process. This would generate an estimated cost saving of $160 million annually.

Conclusion: The thermospray process can increase equipment readiness through increased utilization of the estimated $3.6 million in equipment already purchased. What is required is additional official support and serious investigation of future applications. METCO is willing to offer its support to any and all agencies to further the controlled use of these processes.

SESSION III

MAINTENANCE ANALYSIS SYSTEMS

CHAIRMAN: D. V. MINUTI
NAVAL AIR DEVELOPMENT CENTER

SIMULATION OF TRACK MAINTENANCE COSTS

Richard L. Smith
Allan I. Krauter
Shaker Research Corporation
Northway 10 Executive Park
Ballston Lake, NY 12019

The Simulation Cost Model (SCM) provides economic evaluations for maintenance of systems, components, or assemblies. The application of this technique for costing maintenance operations of track and its component structures is described. Examples are provided which illustrate the use of maintenance action diagrams. These diagrams graphically represent the system being modeled.

The SCM procedure allows separate maintenance cost entries to be associated with definable track substructures such as rail, cross ties, or ballast. In this manner separate tabulations of maintenance expenditures can be obtained from the computerized technique. The SCM also allows time-dependent cost estimating and produces costs by year for: class of track, component or substructure repaired, type of maintenance operations, labor, material, equipment, delays, scrap, fines, etc.

The track SCM computer program is tailored specifically for track maintenance cost analysis, but user flexibility is built in and any maintenance operation which can be depicted through use of a "maintenance action" diagram can be analyzed.

Key words: Computer simulation; life cycle costs; maintenance, track; simulation cost model; track maintenance planning; track standards.

INTRODUCTION

The actual total cost of maintaining a segment of railroad track is extremely difficult to ascertain. At the point of manufacture, a length of rail, a tie, or a ton of ballast has, at a given instant, a fixed determinable cost. However, materials of repair are only a fraction of overall maintenance expenses. Costs of inspection, delivery, installation, and resulting delays must also be considered.

The task of costing any proposed maintenance practice or policy modification is complicated by:

- the fact that there are almost as many maintenance practices as there are railroads to perform them;
- the constant replacement of system materials;

- the unplanned nature of some maintenance operations; and
- the ever-changing demands of business which can alter the physical loading of the track structures themselves.

These problems have prompted several attempts in recent years to improve the techniques for estimating task maintenance costs. Several of these were reviewed recently at a workshop [1]* on the subject of track maintenance. Table 1 is a summary of techniques being used today for evaluating track maintenance costs of performance. The simulation cost model (SCM), the last entry in the table, differs from the more typical techniques in that it provides a

- graphic representation of the system being simulated through use of a maintenance action diagram;
- evaluation of proposed alternate maintenance action policies or procedures;
- listing of all annual track maintenance costs including those for several different subcategories; and
- time simulations to predict future maintenance operations and associated costs.

Simulation cost modeling is described in detail in [2-4].

DEFINING TRACK MAINTENANCE FOR A SIMULATION

Track maintenance costs can be defined as the annual direct charges for the upkeep of track property and equipment. Track property includes rail, cross ties, ballast, and associated hardware fastenings. Equipment refers to those pieces of machinery used for inspecting, installing, and keeping the track in satisfactory operating condition. Although some maintenance operations are performed by every railroad, there are many different ways to perform typical major tasks of track repair. Each railroad has its own maintenance policy which has usually been derived from many years of experience.

In applying the SCM method for determining track maintenance costs it was desired that:

- the technique be applicable to a variety of railroads' maintenance of way operations;
- the procedure allow for cost comparison of alternate maintenance operations, either actual or potential.

The approach taken centers around a general computerized simulation procedure which can handle any user-defined maintenance system. The program uses a standard fourth order integration technique to simulate future maintenance actions. This integration technique can handle

*Numbers in brackets denote references.

costs and maintenance operations which are time varying, nonlinear, or interdependent. A Weibull distribution is used to describe the rate at which the components become defective. Figure 1 shows conceptually how the time integration process operates in the SCM.

Costs which the model can consider include:

- labor cost to inspect an arbitrary number of track components
- labor cost for an arbitrary number of track components
- equipment cost to inspect an arbitrary number of track components
- material costs of new components installed
- cost of track inspection labor and processes
- supervisory labor in monitoring subcontracted maintenance
- fines accrued for deficiencies in track safety
- delays of trains caused by the maintenance repair crews
- slow order delays from insufficient maintenance
- return costs from scrapping components of system
- subcontracted maintenance of the components
- delivery costs of transporting new (renewed) components
- travel and living associated with repairs
- cost of heavy equipment needed to perform repairs
- cost of fueling or powering certain pieces of equipment
- accident costs resulting from maintenance deficiencies
- costs of converting jointed rail to welded rail
- track idling costs

Simulation cost modeling can address questions of:

- How much does it cost to maintain track?
- What are the cost breakdowns within the maintenance system by structural component (e.g., rail, cross ties, or ballast)?
- Where in the maintenance system are the most costly procedures?
- What savings in annual maintenance can be expected if modeled operations are altered?
- What will be future maintenance costs if the system work volume or operations are changed?

Maintenance costs are available for output at any time point in the simulation process. This "snap-shot" of maintenance repair costs and system rates of repair can be used to compare with past or present accounting records of the railroad system being modeled.

SIMULATION TECHNIQUE

The Simulation Cost Modeling technique consists of a graphic diagram of the track maintenance system being modeled, the associated data, and the FORTRAN computer program. The maintenance action diagram is a qualitative representation which is constructed by the user and describes the maintenance actions (inspection and repair) and their relationships to one another. The data set is the quantitative repre-

sentation of the action diagram. Linking these is the computer program. The program quantifies the modeled actions shown in the diagram, implements the associated data set, and provides a selected set of cost outputs.

Maintenance Action Diagrams

The SCM representation of the maintenance system takes the form of a pictorial action diagram which describes how the railroad maintains its track. The maintenance action diagram is analagous to a diagram of a water pipe network. Water systems can be represented by drawings which show the various connecting or branching points as well as their distribution pattern. In a similar fashion the cost model maintenance action diagram displays the system being represented. The user represents pictorially the way in which a railroad (or the industry as a whole) maintains its track. The maintenance actions occur on paths (lines with arrowheads) which are linked together. The paths indicate the order in which these actions are carried out and the order in which the computer carries out its cost computations. The simulation cost modeling procedure calculates the cost for each individual maintenance action represented and thus the total cost to maintain the track system under consideration.

A simple example of a maintenance action diagram is shown in Figure 2. The figure contains shaded blocks in which track exists in a conceptual sense. Track leaves the in-use block because of track inspections which occur on path 1. Track which fails this inspection is separated from the remainder of the track at node (3) and is sent for maintenance. This track is either maintained (via path 5) or is slow-ordered (deferred maintenance - path 4). The separation point is node (5). Repair operations occur in the maintenance repair block, after which the track returns to use.

It can be seen that the maintenance action diagram simply identifies the maintenance system. Paths (uncircled numbers) represent actions in the system whereas nodes (circled numbers) represent decision points. At the decision points, the components are separated for the two outgoing paths, each having or leading to different maintenance actions. Further descriptions of concepts involved in a maintenance action diagram are given in Figures 3 and 4.

Typical maintenance action diagrams for track normally contain:

- The "in use" or "in service" portion of the track system;
- The inspection-of-track loop;
- The removal or scrapping of defective system components;
- The act of maintaining the defective track found from a single inspection process; and
- The supplying or bringing of new components to replace those being scrapped from the system.

A more typical maintenance action diagram for track is shown in Figure 5.

Because the diagram treats many components simultaneously, and because of the shorthand notations used, the diagram is at once convenient and misleading. It is convenient in that the overall system may be viewed at a glance, and if the notation is understood, can give an impression of the complexity of its structure. It is misleading in that many of the details of the system cannot be shown explicitly in the display, and may lead the viewer to believe that the model is too simple.

The maintenance action diagram can be as simple or as complex as necessary to suit the requirements of the problem. An example is a remote rework shop where components are sent for repair. If the repair rates and costs are known the details of the maintenance work in the facility might be disregarded and the applied costs be attached only to the maintenance actions as one lump sum or cost per component repaired. Similarly, major maintenance actions might be simulated initially and then updated in more detail at a later time when more information is obtained and/or desired.

Data for Model

Whereas the maintenance system is defined qualitatively by the maintenance action diagram, the system is described quantitatively by the data and by functions associated with the paths. The data consist typically of costs and of rates at which the maintenance system operates. For complex problems these data can be voluminous; consequently, the computer program was developed to

1. Provide the user with an annotated description of the data coded;
2. Allow the user to update the data quickly as new (or more reliable) information about the system becomes available; and
3. Let the user add (delete) associations between data elements without restructuring the whole body of data already established.

The computerized cost data are treated in the analysis under separate categories. These categories are, in general, expandable by the user. The subcategories used in the model discussed include maintenance expenses by:

- Maintenance Action Diagram Path Number
- Major Repair Block Operation (usually a collection of paths)
- Track Structural Component
- FRA Track Classification
- User Identified Cost Descriptor Codes

Sources for costs can be obtained from many different places. Such sources include

- Standard accounting records
- Policy definitions
- Business practices
- Accident records
- Component failure histories
- Standard maintenance practices
- Safety compliance standards
- Published reports

Functions for Data Modification During Simulations

The majority of cost models developed to date lack a method of evaluating the cost effects of certain parametric alternatives. The cost advantages (or disadvantages) in terms of track maintenance expenditure caused by higher traffic densities, changes in Federal Safety Standards, or an alternate component design, are not usually handled in the traditional cost modeling procedures. The present model addresses these potential variations in the operating system through user-defined functions.

If a cost or rate of track repair has a known dependence which can be written in terms of parameters in the SCM or of time, then use can be made of several preprogrammed families of functions which will carry out the definable dependencies during the simulation. Seven types of functions are presently incorporated in the track SCM including linear, power, and exponential. These can be "turned-on" through the use of various data codes. An example of turning on the Weibull function and 3 other functions is shown in Table 2.

Track Simulation Cost Results

Results from the SCM are obtained for discrete times as required by the user. At each such time, these results, for each path in the track model, consist of:

1. Simulation maintenance action diagram path number.
2. Track component (i.e., rail, tie, ballast, etc.)
3. FRA track class (1-6).
4. Major repair block or type (such as rail laying, surfacing, etc. For example purposes, 20 separate types were identified.).
5. Cost code (the present example includes the following codes):

    a. material costs
    b. equipment costs
    c. fines
    d. delays
    e. scrap return costs
    f. contracted costs

g. delivery costs
h. travel and living
i. six levels of labor

An example of this output is shown in Table 3.

Simulation results are composed of a set of discrete time outputs as produced from the SCM by the Runge-Kutta integration procedure. An example of such simulation results is shown in Figure 6. These results are for a hypothetical Alpha Railroad having the maintenance system described by the maintenance action diagram of Figure 2. The railroad has 1,000 miles of track whose distribution among the FRA track classes is fairly typical of the rail freight industry. The figure shows the annual and total cumulative expenditure for maintenance on the track of this railroad for a period of 5 years. The base case results shown are for a track characteristic life of 32 years. The modified case results are for a reduction in this characteristic life to 24 years. It can be seen that the increased costs over the 5 year period due to the decreased rail life are substantial. It can also be seen that the cost increase is greatest at the start of the simulation and becomes progressively smaller toward the end of the 5 year period. The nature of this transient behavior can be significant in the consideration of the track and other maintenance systems and the determination of such transients is an important characteristic of the SCM technique. The output costing shown would be typical of the higher wear rates of rail resulting from either more traffic or higher loaded rail cars.

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	ORGANIZATION	PROGRAM USE	COMMENTS
DATA BASED MANAGEMENT/REVIEW	Canadian National Railways	Manpower Planning	Data of past maintenance efforts are converted through regression procedures to forecasting formulas for estimating manpower needs by geographic location in the Canadian National Railway System
	P.A. International	Job Task Planning	Continuous tabulation and updating of projected work for periods of one to four weeks. Identifies through listings the need for people and equipment by regions.
	Conrail	Track Maintenance Management System	Keeps tabs on manhours by maintenance operation during past year. Data from sample 9 miles of track have been kept in detail on a trial basis.
	Southern Railway	Maintenance Planning from track quality indices	Track geometry parameters are measured and correlated with track performance (derailments, rail defects, train delays) and track is identified where scheduled maintenance can be economically justified
	Bessemer and Lake Erie Railroad	Organization of maintenance operations data	Tabulates and records for future reference track repair histories under 110 different accounting codes.
ECONOMIC SIMULATIONS	Pugh Roberts	Analysis of track related safety options	Uses a collection of mathematical equations that describe the various inter-relationships among the safety operational elements of the railroad.
	Shaker Research	Simulates maintenance actions and tabulate cost of track repair	Allows user to simulate his own maintenance practices and obtain cost accounting outputs with time. Provides for cost comparison simulations under user defined maintenance practice modifications.

Table 1 Computerized Track Maintenance Programs

PROGRAM REVISION NUMBER :	0006
SCHEMATIC DIAGRAM NUMBER :	0001
DATA FILE NUMBER :	0001
NUMBER OF TRACK CLASSES :	2
NUMBER OF TRACK COMPONENTS :	2
PATHS IN SCHEMATIC DIAGRAM :	18
NODES IN SCHEMATIC DIAGRAM :	9
TIME SIMULATION BEGINS AT YEAR :	0.00
TIME SIMULATION ENDS ON YEAR :	1.90
TIME INCREMENT SIZE IN YEARS :	0.10

WEIBULL DISTRIBUTION PARAMETERS

CLASS	COMPONENT	AVG. AGE	BETA	C-LIFE
1	1	20.00	2.00	32.00
1	2	20.00	2.00	32.00
2	1	20.00	2.00	32.00
2	2	20.00	2.00	32.00

FUNCTIONS AND SHAPE PARAMETERS ACTIVE

PATH	FUNC.	A	B	C	XO	YO
5	7	2.00D 00	3.90D 01	0.00D-01	0.00D-01	0.00D-01
1	5	2.00D 00	2.00D 00	1.00D 00	6.00D 00	5.00D 00
17	6	2.90D-01	1.00D-01	7.10D-01	0.00D-01	0.00D-01

Table 2 Example of Using Modifying Functions

TRACK MAINTENANCE COST

RUN NUMBER : BASE MOD 2
DATE : THU, AUG 14 1980
PLACE : SHAKER RESEARCH CORP

SIMULATION TIME: 0.00

POPULATION IN USE	CLASS	COMPONENT	QUALITY
700.00	1	1	0.10000
50.00	1	2	0.10000
100.00	2	1	0.10000
150.00	2	2	0.10000

NODE	PATH	CLASS	COMPONENT	QUALITY	PATH FLOWS MILES/YEAR	MAINTENANCE DOLLARS
1	1	1	1	0.100000	700.00	210000
1	1	1	2	0.100000	50.00	15000
1	1	2	1	0.100000	100.00	30000
1	1	2	2	0.100000	150.00	45000
2	2	1	1	0.000000	630.00	0
2	18	1	1	1.000000	70.00	0
2	2	1	2	0.000000	45.00	0
2	18	1	2	1.000000	5.00	0
2	2	2	1	0.000000	90.00	0
2	18	2	1	1.000000	10.00	0
2	2	2	2	0.000000	135.00	0
2	18	2	2	1.000000	15.00	0
3	17	1	1	1.000000	8.00	24000
3	17	1	2	1.000000	1.00	3000
3	17	2	1	1.000000	1.00	3000
4	3	1	1	1.000000	70.00	0
4	3	1	2	1.000000	6.00	0
4	3	2	1	1.000000	11.00	0
4	3	2	2	1.000000	15.00	0
5	5	1	1	1.000000	70.00	0
5	4	1	1	1.000000	8.00	200000
5	5	1	2	1.000000	5.00	0
5	4	1	2	1.000000	1.00	25000
5	5	2	1	1.000000	10.00	0
5	4	2	1	1.000000	1.00	25000
5	5	2	2	1.000000	15.00	0
6	6	1	1	0.000000	70.00	1260000
6	7	1	1	0.500000	140.00	1099700
6	6	1	2	0.000000	5.00	430000
6	7	1	2	0.500000	10.00	70000
6	6	2	1	0.000000	10.00	450000
6	7	2	1	0.500000	20.00	276000
6	6	2	2	0.000000	15.00	1290000
6	7	2	2	0.500000	30.00	30994
7	9	1	1	0.166667	84.00	0
7	8	1	1	1.000000	56.00	0
7	9	1	2	0.166667	6.00	0
7	8	1	2	1.000000	4.00	0
7	9	2	1	0.166667	12.00	0
7	8	2	1	1.000000	8.00	0
7	9	2	2	0.062500	16.00	0
7	8	2	2	1.000000	14.00	0
8	11	1	1	0.000040	70.00	0
8	10	1	1	1.000000	14.00	-139972
8	11	1	2	0.000040	5.00	0
8	10	1	2	1.000000	1.00	-9998
8	11	2	1	0.000040	10.00	0
8	10	2	1	1.000000	2.00	-19996
8	11	2	2	0.040005	15.63	0
8	10	2	2	1.000000	0.37	-3749
9	12	1	1	0.102596	78.00	0
9	12	1	2	0.166694	6.00	0
9	12	2	1	0.090942	11.00	0
9	12	2	2	0.040005	15.63	0
					TOTAL $	5312979

Table 3 Example of SCM Output at a Discrete Time Point

TRACK MAINTENANCE COST SUMMARY

RUN NUMBER : BASE MOD 2
DATE : THU, AUG 14 1980
PLACE : SHAKER RESEARCH CORP

SIMULATION TIME: 2.00

COST CODE	MAINTENANCE COST
31	2128810.42
32	34963.76
33	0.00
34	399331.18
35	-82700.33
36	13162.15
37	6993.17
38	13986.42
39	0.00
40	13986.42
41	13986.42
42	34576.45
43	406825.09
44	6993.17
ANNUAL TOTAL :	2990914.31

CLASS	MAINTENANCE COST
1	1972324.34
2	1018589.97
ANNUAL TOTAL :	2990914.31

COMP-ONENT	MAINTENANCE COST
1	2083623.55
2	907290.76
ANNUAL TOTAL :	2990914.31

REPAIR BLOCK	BLOCK COST
1	2220938.07

Table 3 (Continued)

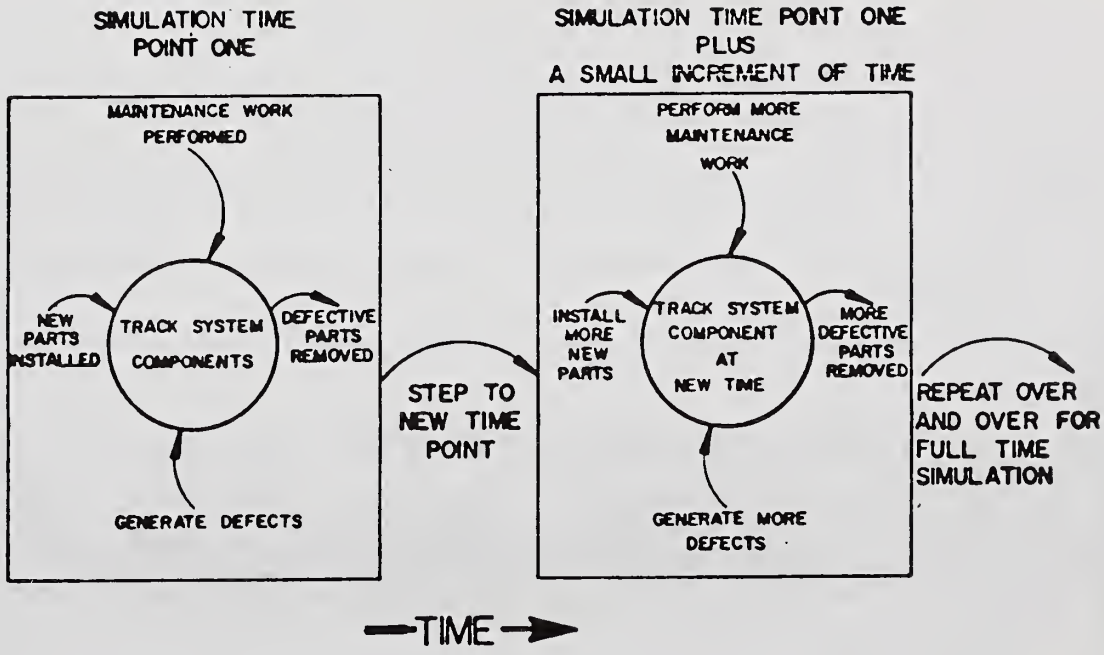


Figure 1 Time Simulation Representation Showing Various Actions Affecting the Track System Component Quality

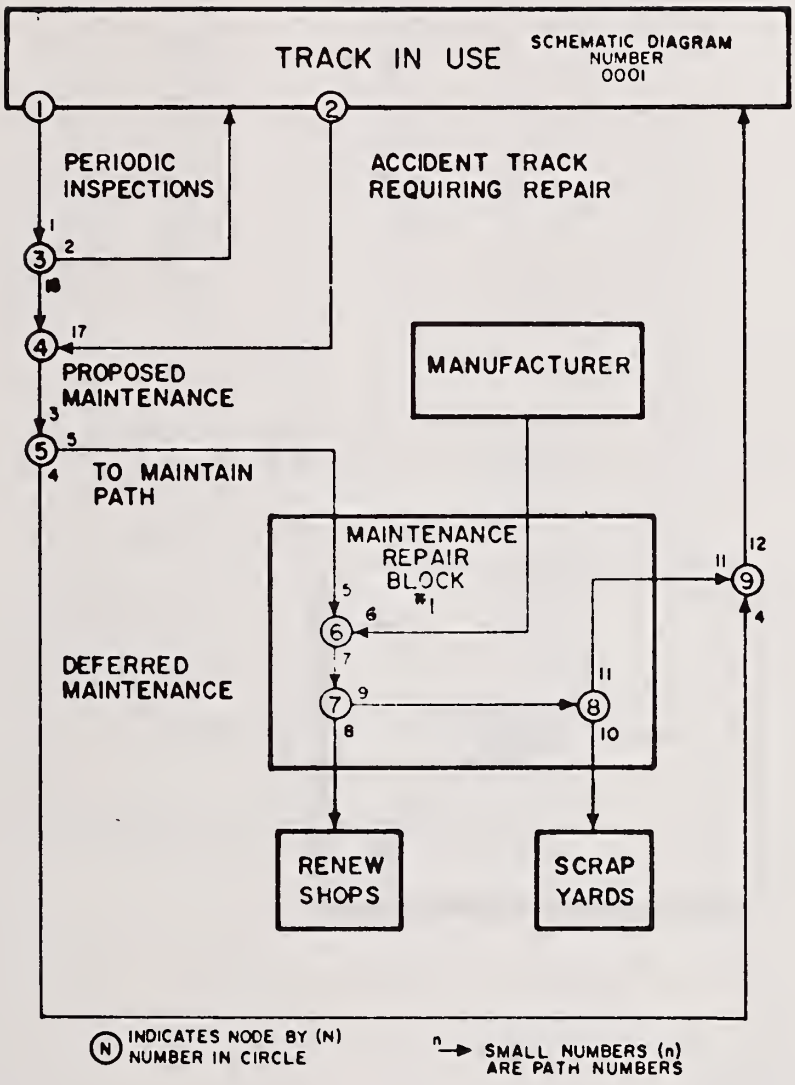


Figure 2 Simplified Maintenance Action Diagram of Track

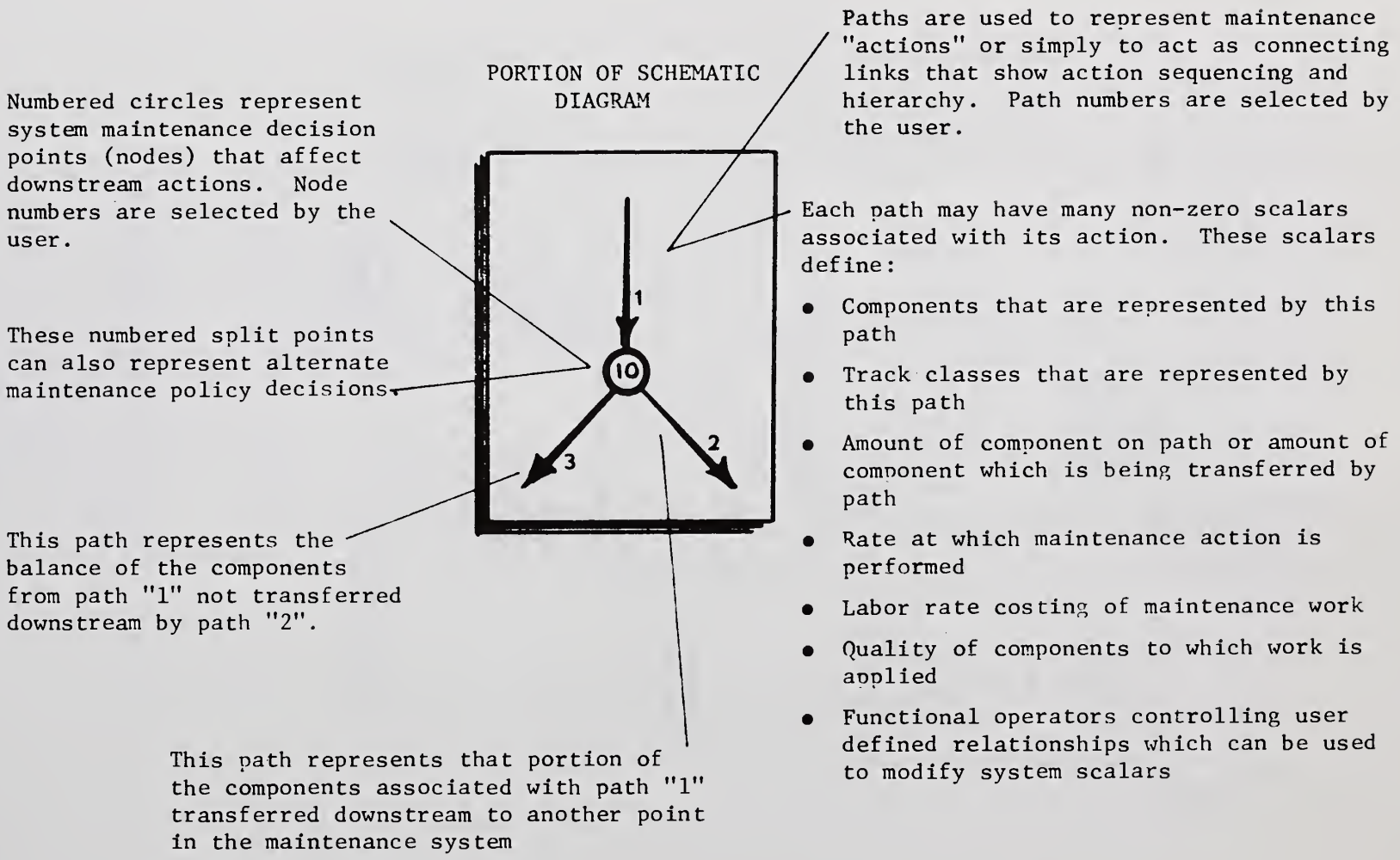


Figure 3 Maintenance Action Diagram Concepts and Notations Used in Numbering Paths and Split Decision Points

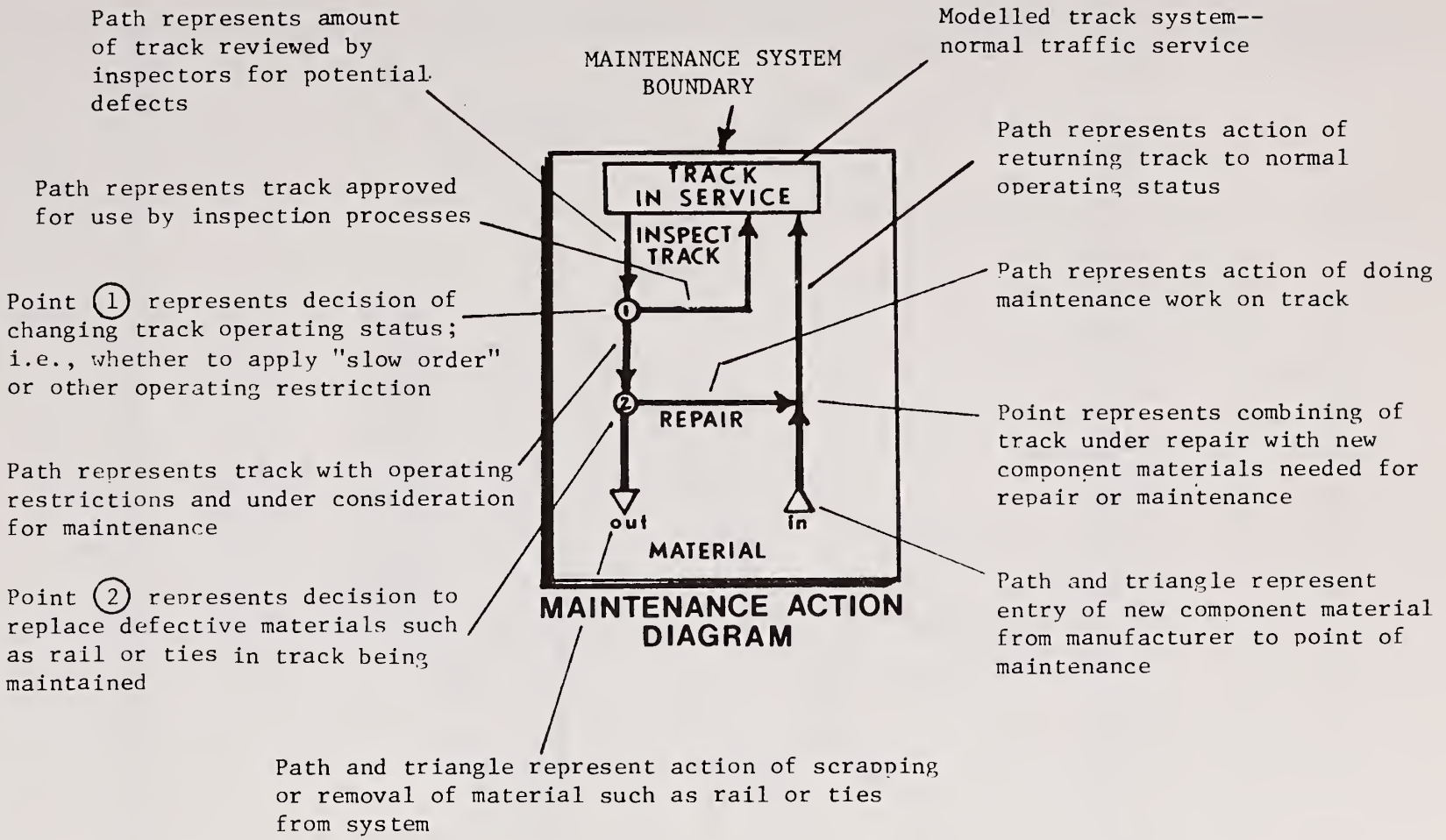


Figure 4 Concepts and Notations Used by Simulation Cost Methodology in Maintenance Action Diagrams

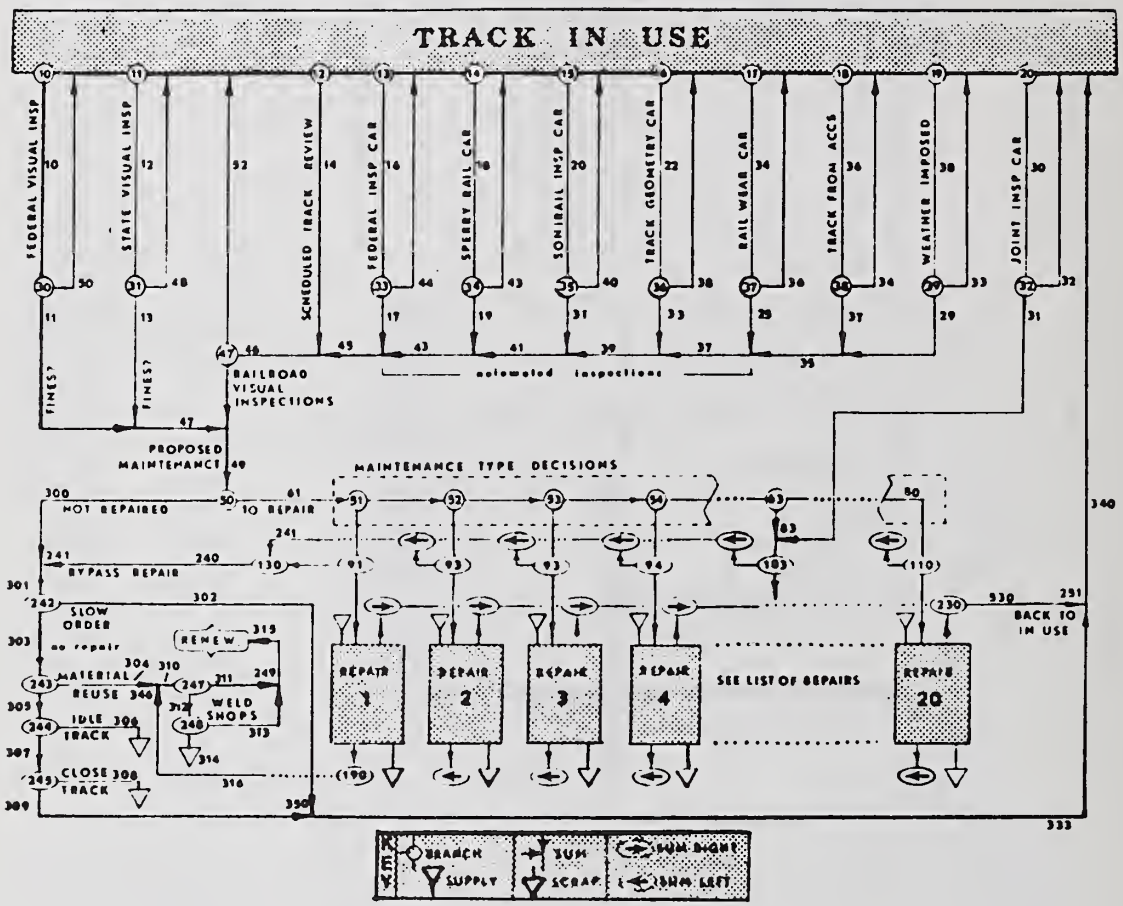
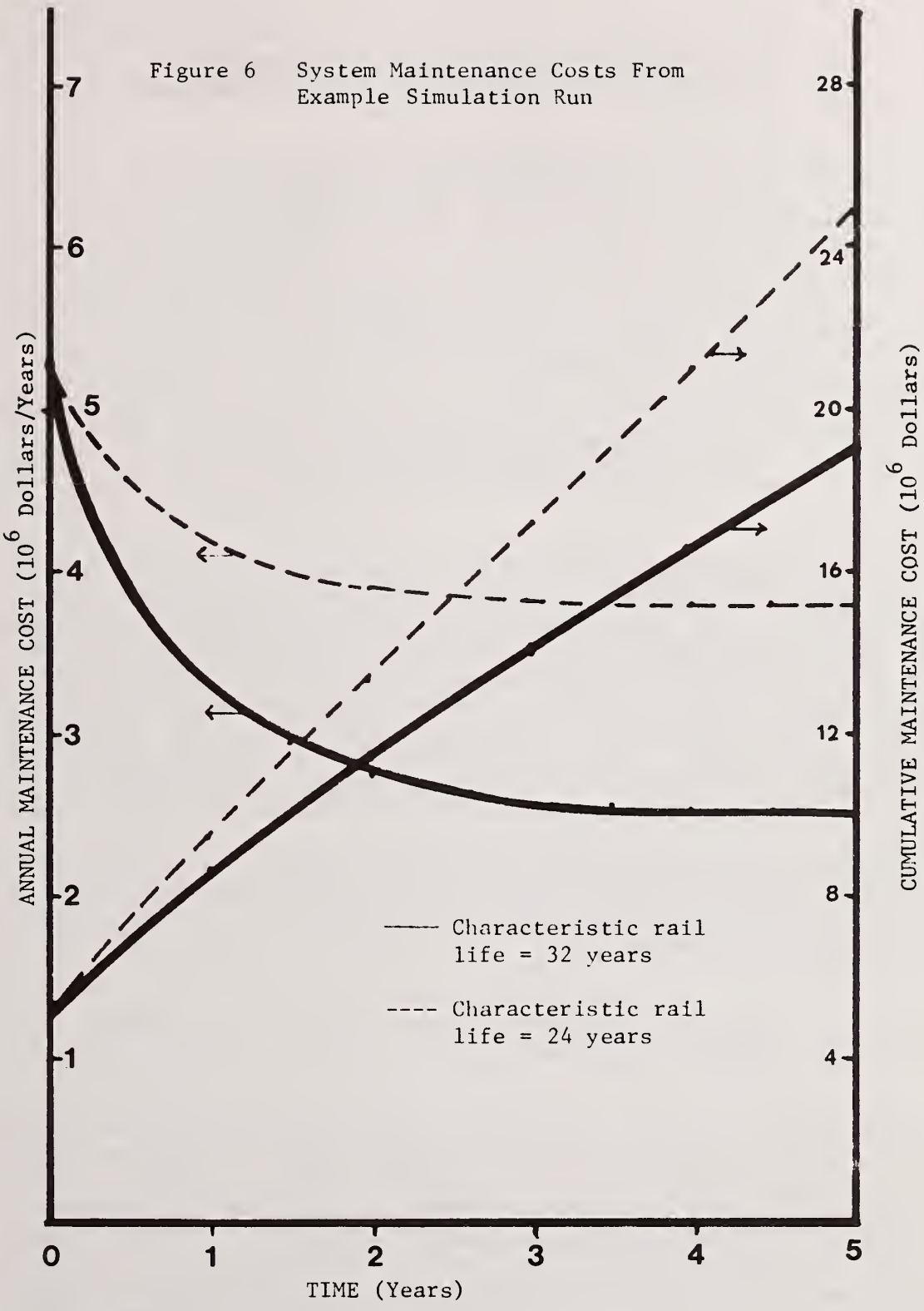


Figure 5 Typical Maintenance Action Diagram for Track

Figure 6 System Maintenance Costs From Example Simulation Run



AUTOMATIC TEST SYSTEM FOR RELIABILITY ASSESSMENT OF GUIDED MISSILE RE-ENTRY VEHICLES

Walter D. Downing, Jr.
Southwest Research Institute
P.O. Drawer 28510, Div. 14
San Antonio, Texas 78284

John P. Pruett
U.S. Air Force
SA-ALC/MMETS
Kelly AFB, Texas 78241

Bryan D. Winn
Southwest Research Institute
P.O. Drawer 28510, Div. 14
San Antonio, Texas 78284

Abstract: A computer-automated test system (ATS) to perform a system level test of guided missile re-entry vehicles (RV) for reliability assessment is being developed for use at Kelly AFB. The ATS is intended to replace the original test complex control system which has been in operation since 1968. During the test, the ATS will control flight environment equipment, deliver discrete signals to the RV and monitor output signals from the RV. Data acquired during the test is used for reliability scoring. This paper gives a brief description of the performance requirements and design solutions being implemented in the new ATS. Emphasis will be given to those areas in which major changes will be made in both hardware and software to take advantage of the experience gained over the several years of testing, as well as those required to provide additional testing capability. The final portion of the paper describes how the data acquired during the test is used in reliability assessment.

Key words: Automatic test system; computer-automated; re-entry vehicles; reliability assessment.

Guided missile re-entry vehicles are subject to mission failures because of the unique requirements under which they operate. An RV incorporates a very extensive set of mechanical and electrical interlocks in order to prevent accidental detonation of the warhead, yet it also must operate with an extremely high degree of reliability. It is by design, a "one-shot" device, stored under silo environments for long periods of time, and must function properly the first time from launch to target. A single component failure could result in a complete mission failure.

Component failures may occur because of the severe altitude and acceleration environments to which an RV is subjected during flight. The chances of component failure are increased by the long periods of silo storage, during which the arming and fuzing components are inactive.

Early in the history of the guided missile weapon system it was realized that there was no program in being for determining the reliability of the re-entry system. As a result of the above situation, Hq USAF directed that Air Force Logistics Command (AFLC) develop an approach for assessing the operational reliability of re-entry systems throughout their operational life. Due to San Antonio Logistics Center's (SA-ALC) assigned responsibility for logistics management and support of weapons, the Directorate of Special Weapons (DSW) was tasked with development of a reliability assessment effort. A feasibility study of alternate approaches was conducted and submitted to Hq AFLC and Hq USAF. Concurrence with the study was received and resulted in issuance of a "Plan for the Assessment of the Reliability of Air Force Arming and Fuzing Systems and Re-entry Vehicles in the Operational Inventory" in September, 1962.

The plan was first implemented on the MK3 re-entry vehicle in 1962. Since no test capability was then available at SA-ALC, this effort was conducted under contract with the development contractor. The original feasibility study proposed establishment of an independent USAF testing capability for all re-entry vehicles. Therefore, concurrent with the contractual evaluation of MK3, a separate study of test equipment for all the then operational USAF re-entry vehicles was placed on contract with a major supplier of automated test equipment. The contractual effort culminated with the delivery and installation of equipment giving SA-ALC a full range of testing capability.

The current contract with Southwest Research Institute is to develop a prototype automatic test system to update the test complex for the MK12 re-entry vehicle. The existing test complex consists of seven (7) functionally related components: the computer system, an automatic test set, two (2) centrifuge systems, a programmable pressure generator, an instrumentation recording system and several support systems. Many of these components are old, obsolete and becoming an increasing maintenance problem. The main task of the current contract is to replace the components of the test complex which are obsolete with updated equipment. To accomplish this goal, the existing computer system and automatic test set will be replaced with a new test console and the existing centrifuge controllers will be replaced with new control consoles. In both instances, the new equipment is being designed to interface with the remaining test complex equipment with a minimum amount of rewiring. In addition to the replacement of major components of the test complex, the current contract requires modification of some of the support systems and the instrumentation recording system to provide improved test capability.

The new test console will provide the functions required to target the RV, sequence the test and control the instrumentation recording system, under the control of the functional test program. The console is composed of a Digital Equipment Corporation (DEC) PDP-11/23 microcomputer system with ROM based application software, I/O interface circuitry and an operator's control and display panel. The test console will utilize power FET's to deliver high energy activation pulses to the RV and opto-couplers on inputs to provide isolation protection from transients in the centrifuge arm wiring or the slip ring interface. A major drawback to the existing test complex is the lack of indication of the progress of the test program. The new test console will provide visual indication of the test status, under program control, and the occurrence of important signals, captured on a visual annunciator system. A video tape recording system is being provided to record events versus time so that in the event of a failure, the video tape may be played back and analyzed for error assessment. The test console includes an uninterruptible power supply.

The functional test program is divided into states which are related to the different stages of the test. The program requires operator intervention in the form of a pushbutton entry initiated interrupt before proceeding to the next state. Interrupts are selectively enabled by the program in order to prevent erroneous entry into a state at the wrong time. Status lights prompt the operator as to when an entry is required. Numerical entries for targeting function settings are made via thumbwheel switches on the test console. All operator interaction is provided by the test program without the need for a system terminal.

Since hardware failures such as component failure, interconnection failure and power failure could cause catastrophic errors, the test program includes certain safety and tolerance checks. In the event of test equipment failure the program sets itself in a hold state, alerts the operator and awaits instructions to continue or abort the test. The options also include the capability to run a portion of the test again. These provisions were added because previous testing experience indicates that if at all possible, a test should be allowed to continue to completion and to gather as much data as possible.

The most difficult problem in developing the test program software was in providing for fault tolerance. Reference was made in earlier paragraphs to using ROM based software and reduction of operator error, both of which reduce the possibility of program error. In addition to these provisions, the test program also tries to reduce faults resulting from improper branching. To accomplish this the program tries to limit any branching in any critical areas of the test. When branching is required, the program performs an additional check to insure the execution of the proper code. A combination of software and hardware flags are used to provide the additional checks. After major branches, the program contains an allowable time for operator intervention. All

waiting loops contain multiple exit conditions, including a time-delayed interrupt which is generated by a programmable clock module.

The centrifuge control consoles provide the functions for a programmed run of the selected centrifuge from a table of g versus time values entered by the operator. The centrifuge control console is also composed of a PDP-11/23 microcomputer with ROM based application software, I/O interface circuitry and an operator's control and display panel. The system will utilize multiple EPROM boards to contain g versus time tables for routine flight profiles. Each profile is addressed at the same 2K word "window" of memory, via standard DEC control registers. The operator also has the option of writing a new table directly into RAM from the system console, after which the table may be executed, saved on EPROM or punched on paper tape. The centrifuge control consoles provide complete manual backup. Centrifuge speed, as indicated by a shaft encoder, will be measured by an F/V converter in the analog control loop and by a programmable counter module in the computer system. The control program will make a frequency measurement at high speeds, but will convert to a period measurement at low speeds.

The centrifuge control program is somewhat different from that of the test set. Like the test program, the control program is divided into states, but in this case the states represent different modes of operation. The different modes are: profile building, manual operation and automatic operation. The profile building mode is used to enter the g versus time tables. The manual mode only provides display support for operator information. The automatic mode is a program controlled run using the values of a g versus time table as setpoints for the flight profile.

Hardware generated interrupts are used in the control consoles to insure safe operation of the centrifuge. A crystal controlled clock generates interrupts at .5 msec (for setpoint calculation), 1 msec (for speed measurement), 10 msec (for test console support update) and 500 msec (for display update). Runaway checks will be performed by the program which limit the measured speed to 110% of the setpoint. Loss of line power generates an interrupt which will put the control program into a waiting state after the centrifuge has coasted to a stop.

Fault tolerance provisions in the control programs do not include extensive branch checking due to the absence of significant branches in critical areas of operation. Software checks are provided to insure accurate profile execution. The control program also provides emergency stopping capability.

Support systems being updated during the current contract include the simulation system, the radar test system and mechanical accelerometer test system. The simulation system is being updated to incorporate a resettable on-board simulator constructed from actual RV components. This is an improvement over the present method of simulation by

generating the simulated RV signals external to the centrifuge arm wiring. The radar test system is being updated to incorporate remote programming from the test console. In the present complex all components of the radar test system are on the centrifuge arm, and data is being lost during some runs. The mechanical accelerometer test system is being updated to provide recaging capability. The mechanical accelerometer should be recaged after testing before the RV is removed from the test complex in order to prevent the mechanical movement in the device from slamming into the stops.

The testing of RV systems for reliability assessment presents unique problems in data acquisition, i.e., the data is available for recording only once and in some cases comes and goes in microseconds. Therefore, instrumentation of demonstrated reliability and accuracy is chosen. Signals are prioritized into levels of importance, i.e., signals affecting overall system performance have the highest priority of measurement, with component data being secondary. For system level tests, it has been found that a good mix of digital and analog instrumentation should be used. The updated test complex will utilize the following instrumentation:

Analog:

CRT Visicorder (2 ea.)	- 50 channels
Tape Recorder	- 14 channels
Oscilloscopes (2 ea.)	- 4 channels

Digital:

Minicomputer based data acquisition system with A/D converter and digital voltmeter	- 32 channels

Reliability assessment is accomplished by selecting a representative sample of the population, testing the sample and finally through statistical analysis making an inference about the total population. The validity of the process is dependent on the integrity of the sampling since all statistical theory is based on a random selection from the population. Stated simply, in making a random selection every member of the population must have an equal opportunity of being selected.

Statistical theory determines the number of samples required for reliability assessment. Normally the larger number of samples available the more confident the resulting assessment. Initially, this test program required a large sample size dictated by use of classical statistical methodology and one-time use of test data. The expense involved in this approach led to development by SA-ALC of the current Bayesian statistical technique and aggregation of test data. These measures permitted a

reduction in sample size to 24 samples per year. This sampling level, if no failures occur, will permit an assessment of 90% reliability at 90% confidence. Combination of successive annual test quantities support higher numerical estimates.

REDUCTION OF TEST EQUIPMENT PROLIFERATION WITH THIRD GENERATION ATE

S. Perra
RCA Corporation
Burlington, MA 01803

Abstract

Conventional ATE systems use discrete test instruments to measure each parameter. Third generation ATE exploits the full computational capabilities of the system computer to evaluate test parameters by applying such techniques as Fast-Fourier transformers, digital filtering, statistical analysis, list sorting, and least-squares curve fitting. Hardware-associated errors such as those introduced by lead length, gain and offset, and A- to D- converter non-linearity are corrected automatically by calibration software routine on a sample-by-sample basis.

Similarly, the system also has the capability which allows the user to create complex stimulus waveforms using the computer. Thus, any number of waveform types (classical, complex or arbitrary waveforms) can be generated by computer algorithms.

This basic stimulus ans measurements capability forms a third generation core system, which when augmented with special front-ends, such as hydraulic/pneumatic, electro-optical and motion, provides an optimum solution to meeting avionics testing requirements.

The result is less peculiar test stations with less measurement and stimulus hardware, and thus more reliability, less calibration, and more flexibility to meet future needs.

THE DEVELOPMENT OF AUTOMATED TEST PROCEDURES FOR COMPLEX ELECTRO-MECHANICAL SYSTEMS

R.E. Hartwell
RCA, Government Systems Division
Automated Systems
P.O. Box 588, Burlington, Massachusetts 01803

Abstract: Systems which are partly mechanical and have significant electrical controls, drives and testing/monitor points are well suited to automatic testing. The use of a microprocessor controlled test system permits improved test strategy, with sophisticated measurement processing, rapid test step execution, and program controlled interactive messages to the mechanic. This paper discusses design methods and techniques which lead to improved tests. The turret stabilization and fire control system of a modern combat vehicle are used in an example of automated test development for complex, interactive, electro-mechanical systems. Quantitative and qualitative techniques are presented, as used in developing test strategies for that vehicle, and for evaluating the effectiveness of the test programs and their validation in actual fault isolation exercises.

Key words: Automated test equipment; fault isolation diagnostics; functional subsystem; line replaceable units; malfunction; microprocessor controlled test set; symptom; test strategy.

BACKGROUND

The M1 Tank and the Infantry/Cavalry carrier Fighting Vehicle System both have a mixture of sophisticated weapons control and conventional automotive electrical systems. A microprocessor controlled automatic test system has been developed for on-vehicle testing and fault isolation diagnostics. The testing techniques developed on this Simplified Test Equipment M1/FVS (STE-M1/FVS) project are presented in this paper.

Military mechanics are the end users of the STE-M1/FVS, and they are not skilled in the interpretation of electrical schematics, nor are they expected to perform complex technical evaluations. The test set must provide comprehensive instructions to the mechanics, make measurements at electrical test point interfaces, and sequence test steps to achieve effective and comprehensive testing.

MISSION

The test programs encoded in the test set must be able to achieve testing for the majority of the electrical and electronic subsystems on the vehicle. The mechanic, with the test set, must be able to determine GO or NO GO conditions for each testable subsystem, and when the NO GO condition is detected, fault isolation to the "Line Replaceable Unit" (LRU) is necessary. In the Army, this is the Organizational Level of Maintenance, conducted by teams of mechanics stationed at the company and battalion level of armored and infantry units.

OBJECTIVES

The design of both the test set hardware and its encoded test programs must achieve certain elementary requirements for field user acceptance. It is strongly desired to encourage the use of effective and reliable maintenance procedures, to avoid "best guess" replacement techniques. The guessing game has been costly to the military for vehicles of comparative simplicity. With sophisticated weapons and fire control systems, a disciplined maintenance approach is essential.

Another objective is to reduce the incidence of disconnecting vehicle harnesses in the process of testing. The use of built-in test connectors is of great value in this respect. M1 and the FVS vehicles have several multi-pin test connectors, through which electrical measurements are made in the initial steps of all diagnostic investigations. Vehicle harnesses are not disconnected until tracing faulty signal paths in the final stages of fault isolation.

A further very important objective is to reduce the need for printed charts and instructions; that is to reduce the reliance on written technical manuals. An automated test set cannot eliminate the need for these manuals, especially the need for pictures and graphics. Well coordinated planning of both test set and manuals is needed to achieve an effective diagnostic capability.

TWO VIEWPOINTS OF THE VEHICLE AS A SYSTEM

There are two distinct ways of viewing the vehicle as a system, and this has led to confusion and complications in the design of diagnostic test procedures for these vehicles. In the first instance, the vehicle is seen as a network of physical boxes (LRUs) connected by cable harnesses, as shown in Figure 1. This is the perception of the vehicle to its manufacturer and to the provisioner of spare parts; it is the image of the vehicle portrayed in the mechanical drawings package. Unfortunately, this hardware module viewpoint is greatly at variance with the image of the vehicle as perceived by the crew.

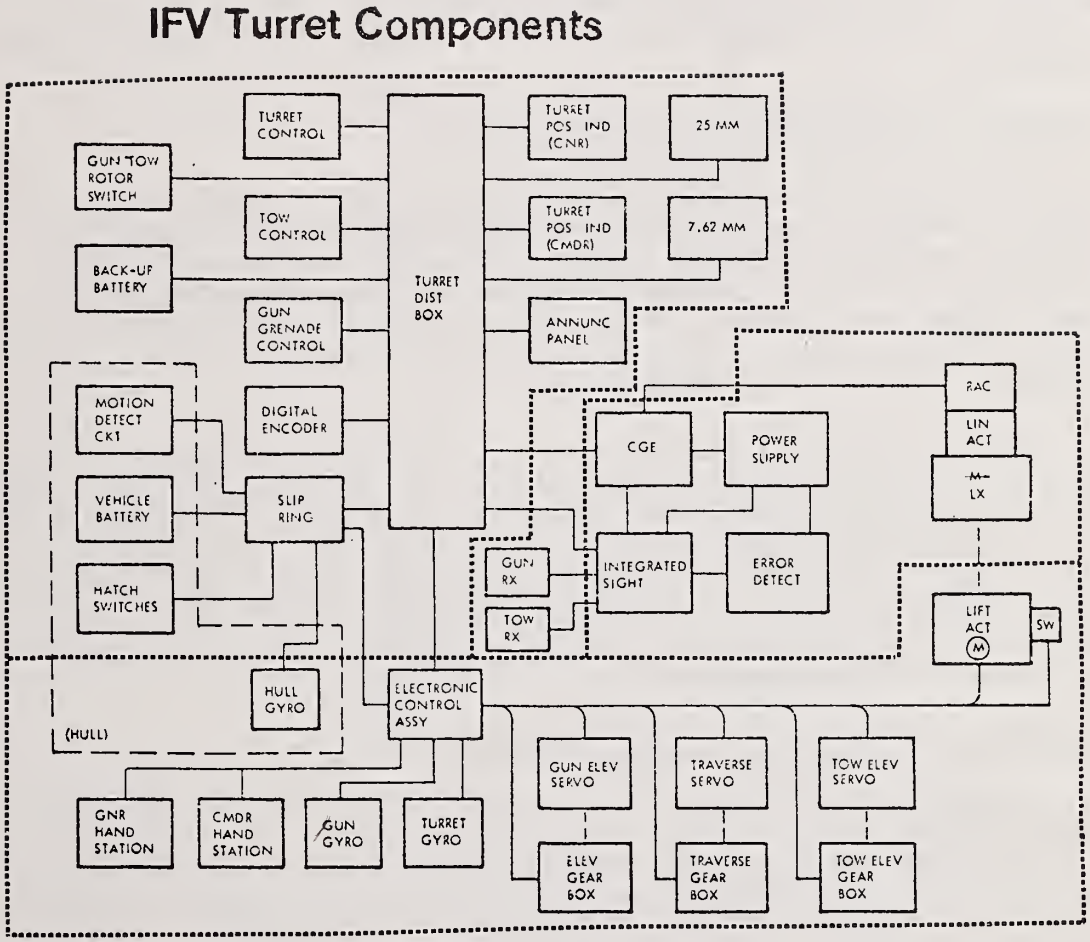

IFV Turret Components
TURRET CONTROL
GUN TOW ROTOR SWITCH
TOW CONTROL
BACK-UP BATTERY
GUN GRENADE CONTROL
TURRET DIST BOX
TURRET POS IND (CNR)
25 MM
TURRET POS IND (CMDR)
7.62 MM
ANNUNC PANEL
MOTION DETECT CKT
DIGITAL ENCODER
VEHICLE BATTERY
SLIP RING
HATCH SWITCHES
CGE
POWER SUPPLY
RAC
LIN ACT
M-LX
GUN RX
TOW RX
INTEGRATED SIGHT
ERROR DETECT
LIFT ACT
SW
HULL GYRO
(HULL)
ELECTRONIC CONTROL ASSY
GUN ELEV SERVO
TRAVERSE SERVO
TOW ELEV SERVO
GNR HAND STATION
CMDR HAND STATION
GUN GYRO
TURRET GYRO
ELEV GEAR BOX
TRAVERSE GEAR BOX
TOW ELEV GEAR BOX

Figure 1.

To the users, the vehicle consists of functional subsystems which perform a number of missions. The aiming of weapons, the firing of weapons, the stabilization of weapon platforms, and the provision of safety, comfort, and support are crew related functions. The crew is intimately concerned with the normal or abnormal operation of the functions. Failures in the vehicle hardware are eventually perceived as the loss of one or more normal vehicle functions. Failure conditions can, in fact, be described at three levels of abstraction; hardware fault, malfunction condition, and symptom description. The failure itself is imbedded in the hardware module or cable at the instant of physical breakdown. The crew eventually experiences the failure as a loss of normal performance, or the malfunction condition. The crew perceives and then reports the situation, which gives rise to the symptom description. Figure 2 shows a relationship between these levels of fault perception.

STATEMENT OF OBJECTIVES FOR EFFECTIVE TESTING

Recognizing that the crew senses the physical failure condition as the loss of a vehicle function, the test procedures should, in some way, relate to functional aspects of the vehicle. As any garage mechanic can tell you, the vehicle user's description of symptoms is usually crude, incomplete, and inaccurate. Test procedures must therefore establish, by measurement and observation, what type of malfunctions are present.

This leads to the conclusion that test procedures should be provided for each and every functional subsystem of the vehicle. With such subsystem partitioning, there will be at least one test procedure to check out any suspected or known malfunctioning condition. That test will confirm that performance is defective, or else the test will find a "NO FAULTS FOUND" condition. The ability to run the proper test to find and isolate the fault is simply a matter of selecting the applicable subsystem in which the malfunction has occurred.

WEAKNESSES IN "CONVENTIONAL" TEST STRATEGY

Test procedures have too often been based on the intuitive diagnostic approach which appeals so much to design engineers. The technique is to observe what works and what doesn't, eliminate whole areas of concern based on these symptoms, and make further measurements and observations to branch to successively narrower portions of the circuits which are involved. The first problem with this technique, for adaptation to a computer programmed test set, is that careful and accurate interpretation of symptoms is necessary. The second problem is that system schematics and detailed system operation must be understood by the troubleshooter. Many military technical manuals base their troubleshooting section on large lists of symptoms with corresponding test procedures to be run. Close scrutiny of the symptom lists always shows ambiguity. The test procedures may be correct for the intended

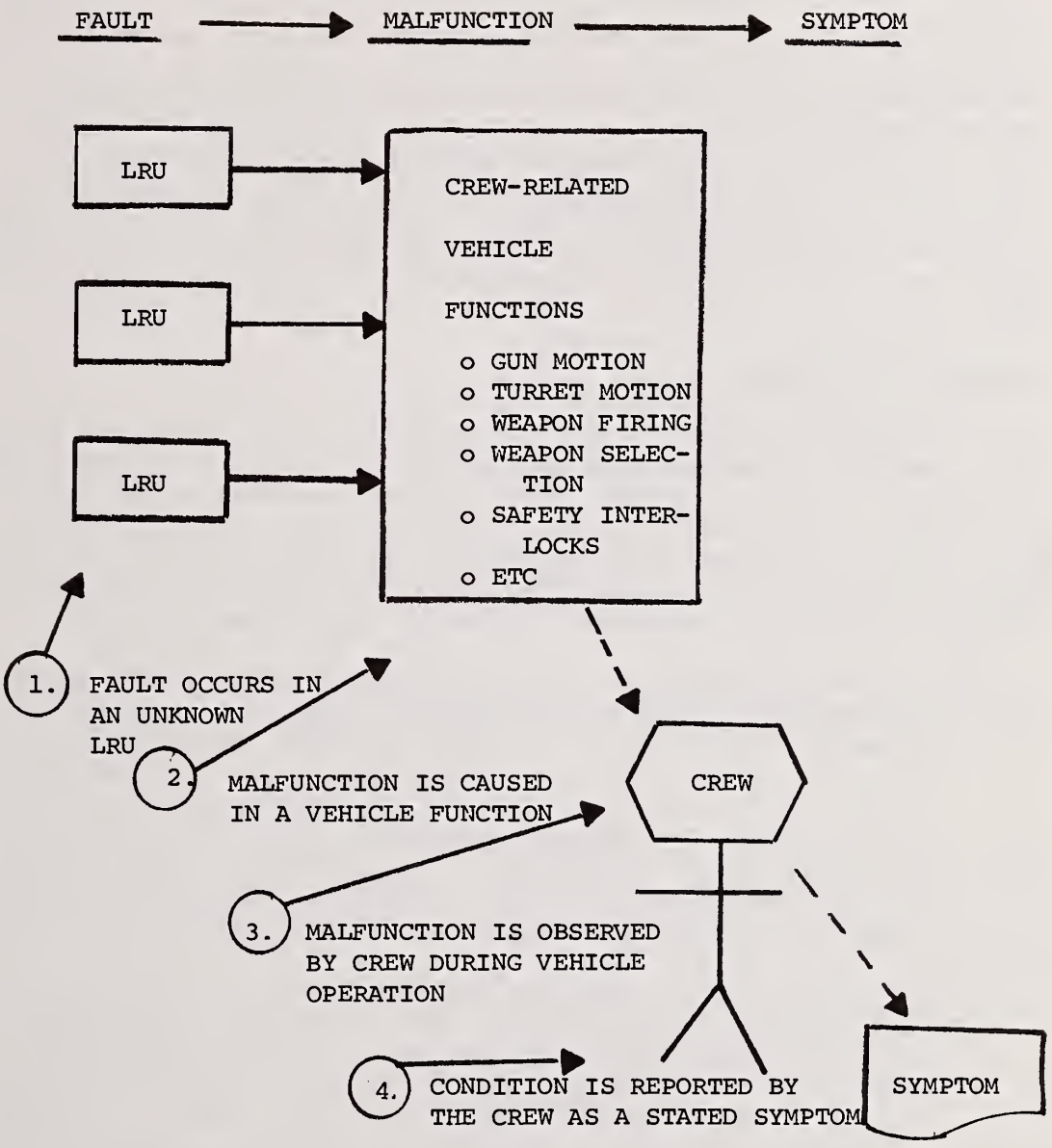


FIGURE 2. PERCEPTION OF MALFUNCTION LEADS TO STATEMENT OF A SYMPTOM

meaning of the symptom, but the test procedure may be very wrong for other conditions which can and will be misinterpreted relative to the symptom as stated.

Other pitfalls must also be noted in the traditional symptom oriented approach. There is often a disregard for prerequisite test conditions. The procedures presume that related or supporting functions are healthy and this can be a fatal error to the diagnostic logic. For example, a presumed gun firing malfunction may be caused by a safety interlock failure. If the interlocks are not checked in the test, there is no hope of reaching the proper diagnostic conclusion. Another serious problem occurs if the test procedure does not have a "NO FAULTS FOUND" exit, and many symptom-oriented test procedures always fault some LRU. Sooner or later some mechanic will run that test procedure even though that symptom is not present, and a healthy LRU will be condemned as faulty.

IMPROVED TEST STRATEGY

Test procedures encoded in microprocessor code in the STE-M1/FVS have taken advantage of computer age technology, to produce more effective diagnostics. Because the test set is fast in execution of the tests, and because it can store large quantities of instruction and procedures, there is freedom in the development of concept, strategy, and scope of these tests. The following design concepts have evolved as the most effective and successful approaches to diagnostic testing:

(1) For test procedure development, the vehicle should be partitioned into functional subsystems. Each subsystem should cover a function which is clearly perceived by the crew as essential to the operation of the vehicle and its various missions. Such subsystem oriented tests can therefore be called upon whenever a suspected problem exists in the operation of that function on the vehicle. As a consequence, the same test can be run as a partial check on vehicle "readiness", since if there are faults in the subsystem, the test should detect them.

(2) The first step in each test must be to establish uniform and consistent initial conditions. No assumptions can be made that other supporting functions are fault free. Checks of power supply sources, and verification of interlock functions, are among the necessary initial conditions checks. Comprehensive and uniform checks on initial conditions assure that the test procedure will arrive at the same test conclusions no matter how many times the test is run.

(3) Measurements are first restricted to test signals at the vehicle's test connectors, without breaking into vehicle cable harnesses. As long as no malfunctioning conditions are substantiated, vehicle harnesses should be left intact. When the measurements and observations firmly establish a malfunction-

ing condition, vehicle harnesses may have to be broken so as to make measurements at these intersections for final resolution of the fault source. The STE-M1/FVS has adapters and "T" connections to permit measurements at harness intersections.

DESIGN TOOLS

A number of tools which have proved beneficial in the development of tests and test strategies are presented at this point. Figure 1 previously showed the network of boxes and harnesses in the Fighting Vehicle System Turret. The list of LRUs and cables is readily available from the vehicle manufacturer, but the synthesis of functional subsystems for the same vehicle are not as readily established. Troubleshooting sections of the vehicle technical manuals tend to be organized in a hybrid relationship, based on functions of the vehicle, and failure-symptom lists. One means to establish functional subsystems is to develop a functional zone chart, as in Figure 3. Here the functions and their overlapping relationships are presented. Some refinement is needed before the chart becomes truly representative of the inter-related functions. Only when the intricate overlap of functions is truly understood, can the logical development of test strategies begin.

Once the subsystems have been established, a test procedure will be developed for each subsystem. A subsystem/LRU Matrix can then be formed, as in Figure 4. In one form of this Matrix, an "X" at the intersection of a subsystem and an LRU means that the LRU can have a fault which leads to malfunction in that subsystem. In further refinement of the Matrix, numbers may appear at each intersection, to indicate the number of fault conditions which the LRU can contribute to cause a malfunction of the subsystem.

The final design tool in the development of the diagnostic test is the test flow chart. In the STE-M1/FVS project, it was found necessary and effective to produce "Top Level" flow charts which completely trace each test through its "GO CHAIN", listing each message to the mechanic and each measurement made by the test set in the process. The "NO GO" paths at each measurement decision branch are simply indicated by listing the possible LRUs which could cause that NO GO condition at that point in the test. The strategy of each test is quite well represented with this level of flow chart, and can be reviewed and revised before full detailed flow chart expansion is attempted.

Detailed flow charts eventually show each and every message and measurement step for the entire test procedure. Such flow charts are the basis for test coding, and serve to document the content of the test. They are essential reference documents during on-vehicle validation of the test procedures. Although space does not permit a detailed description of the flow chart techniques adapted for STE-M1/FVS, I will note that a rigorous set of standards has been established, which results in flow charts which clearly define the essential steps in these proce-

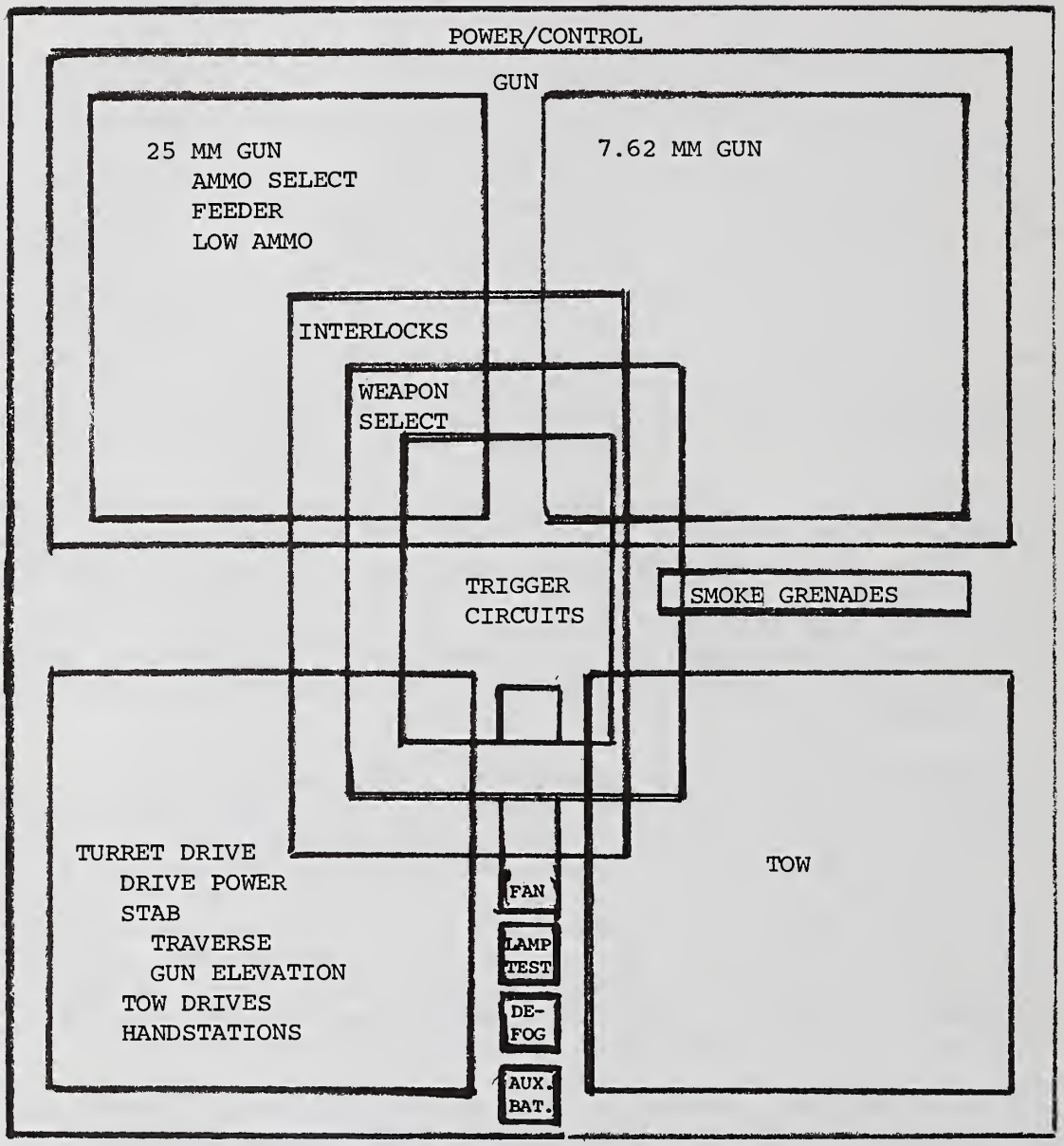


FIGURE 3. FUNCTIONAL ZONES OF INTER-DEPENDENCE
FVS TURRET SUBSYSTEMS

FVS TURRET SUBSYSTEMS

REF DES	LRU	TURRET (GENERAL)									TURRET DRIVE				
		PWR DIST	INTR LOCK	WEAP SEL	TRGR	GUN	TOW CTL	SMK GRD	FAN	TRAV	GUN EL	TOW LFT	TOW EL	STAB
2A1	TDB	X	X	X	X	X	X	X	X	X	X	X	X	X
2A2	AZE		X							X	X		X	
2A3	TCB	X	X				X		X	X	X	X	X	X
2A4	WCB			X	X	X	X	X					X	
2A5	TWB		X				X					X	X	
2A6	ANP	X	X			X	X							
2A7	SLR	X	X							X				X
2A8	CPI		X							X				
2A9	GPI		X							X				
2A10	FNV								X					
2A14	MGS					X								
2A15	GUN					X								
2A20	MGL					X								
2A21	APL					X								
2A22	HEL					X								
2A23	APS					X								
2A24	HES					X								
2A27	RYA	X						X						
2A29	GRL		X											
2A30	TRS		X											
2A31	LGL							X						
2A32	RGL							X						
2A33	GRS										X			
2A34	TRR												X	
2A36	AXB	X												
2A37	AXB	X												
2A100	ISU			X			X			X	X		X	
2A101	CGE						X							
2A103	LNR						X							
2A104	PWC			X			X			X	X		X	
2A200	ECA	X	X		X		X			X	X	X	X	X
2A201	TDA		X		X					X				
2A202	GED		X								X		X	
2A203	TED		X								X	X	X	
2A204	TLM		X									X		
2A205	GHS				X					X	X	X	X	
2A206	CHS				X					X	X	X	X	
2A207	TGY										X			X
2A208	GGY									X	X			
2A209	HGY									X				X

(CONTINUED NEXT PAGE)

Figure 4. LRU/Subsystem Matrix

		TURRET (GENERAL)									TURRET DRIVE					
REF DES	LRU	PWR DIST	INTR LOCK	WEAP SEL	TRGR	TOW GUN	TOW CTL	SMK GRD	FAN	TRAV	GUN EL	TOW LFT	TOW EL	STAB		
2W1	CABLE	X														
2W2	"	X	X											X		
2W3	"	X		X		X		X	X		X			X		
2W4	"	X	X	X		X	X	X	X		X			X		
2W5	"	X	X			X	X				X	X	X			
2W6	"		X				X			X	X		X			
2W7	"	X														
2W9	"					X		X								
2W10	"					X			X							
2W12	"					X										
2W14	"	X														
2W15	"	X														
2W101	"					X	X				X		X			
2W102	"						X			X			X			
2W103	"										X		X			
2W104	"						X						X			
2W301	"	X	X				X			X	X	X		X		
2W302	"	X								X	X	X	X	X		
2W303	"	X												X		
2W304	"		X										X			
2W305	"		X								X			X		
2W306	"		X									X				
2W307	"		X							X				X		
2W308	"	X								X	X	X	X	X		
2W309	"	X												X		
HULL CABLE																
1W13	"		X													
1W17	"		X													
1W18	"		X													
1W19	"		X													

Figure 4. LRU/Subsystem Matrix

Each "X" shows that the LRU (listed at the left) can create one or more failure conditions in the Subsystem (listed along the top).

dures, in terms of the verbatim messages displayed to the mechanic, the test point measurements executed, and the measurement tolerances used in each decision branch.

IMPROVED TEST STRATEGY USING AUTOMATED TEST EQUIPMENT

By combining improved test strategy along with microprocessor technology, diagnostic test procedures have been improved in a number of ways:

- o More measurements can be made in shorter testing time.
- o Tests are more comprehensive (cover more failure modes).
- o Tests are more reliable (conducted from uniform and established initial conditions, they always reach the same consistent results).
- o Vehicle harnesses are not needlessly disconnected in testing.
- o Test set use is encouraged, guessing is discouraged.

POSTSCRIPTS

A number of design factors and program constraints were recognized during the development of STE-M1 and STE-M1/FVS and some of these are enumerated here:

(1) Comprehensive test coverage requires a great amount of procedures to be coded and validated. Formal means to document such procedures and validate these tests as needed.

(2) Software validation aids must be built into the tests. While checking the procedures on-vehicle, the validation team must be able to track the test set and monitor measurement results at each step in the test.

(3) Vehicle use for test program validation is a valuable and scarce resource. Plan for the most efficient possible use of on-vehicle time.

(4) Plan for changes to the test programs (software) during the initial fielding of the vehicle. Changes to the software due to testing considerations as well as to vehicle changes are bound to be needed.

(5) Because a large portion of the test procedures are involved with messages to the mechanic, an appreciable portion of the software changes will, in fact, be "human factors" considerations. A message which is sometimes misunderstood causes test unreliability, as much so as improper test limits.

CONCLUSION

By partitioning the vehicle into a few fundamental subsystems, diagnostic test procedures have been established which prove effective and efficient. There are a limited number of test procedures available, corresponding to functional subsystems with which the vehicle user is intimately concerned and aware. Because the test set is fully programmed under computer control, the large number of measurement and message steps in each procedure can be rapidly executed.

ADVANCED ATTACK HELICOPTER AH-64
FAULT DETECTION/LOCATION SYSTEM

H. E. Pohlenz
Manager, Maintainability Section - Systems Engineering Department
Hughes Helicopters, Incorporated
Culver City, California 90230

Abstract: Army and Hughes Helicopters Advanced Attack Helicopter (AH-64) Program Management have stressed the importance of an effective Fault Detection and Location System (FD/LS) throughout the AH-64 design process. The FD/LS program objectives were to avoid flights with failed safety and mission critical hardware, reduce maintainability downtime and prevent removal and replacement of good hardware. The design approach was to make extensive use of existing AH-64 equipment with Built-in Test Equipment (BITE) added, and to emphasize reliability and maintainability techniques, analyses and tradeoff processes from the earliest stages of the design effort. The resulting AH-64 FD/LS is an optimum mix of hardware (conventional caution and warning devices coupled with microprocessor controlled multiplexing system for data handling and display), Man-in-the-Loop systems operations, and technical procedures and maintenance manuals. Both AH-64 FD/LS test and analysis results indicate that systems objectives and requirements have been met or exceeded.

Key Words: Fault Detection/Location System; Failure Modes and Effects Criticality Analysis (FMECA); Reliability Centered Maintenance (RCM); Caution, Warning and Advisory Panels; Multiplex (MUX) System; Fire Control Computer; On-Condition Monitor; Condition Monitoring; Built-in Test Equipment (BITE); and, Skill Performance Aids (SPA)

INTRODUCTION

The U.S. Army's Advanced Attack Helicopter, the Hughes AH-64, is the first Army Attack Helicopter to be developed specifically for the day/night/adverse weather anti-armor mission. The AH-64 is a tandem seat, two place, twin engine helicopter with a four bladed main rotor system having a 48.0 foot diameter. Equipped with completely integrated aircraft and weapons systems, the AH-64 will acquire and destroy hostile targets at maximum standoff ranges.

The primary point target weapon of the Advanced Attack Helicopter is the HELLFIRE anti-tank missile, with area suppression fire provided by 30 mm cannon and 2.75 FFAR rocket subsystems. The Target Acquisition Designator Sight (TADS) and Pilots Night Vision Sensor (PNVS) provide the day/night/adverse weather target acquisition/designation and Nap of Earth

flight ability which enables the AH-64 to effectively launch its attack armaments from stand-off ranges. The excellent performance characteristics of the AH-64 are highlighted by its demonstrated airspeed of 204 knots, g loads ranging from -0.5 to +3.5 g's, and sideward and rearward flight speeds of 45 knots. Designed for a fifteen year service life, this helicopter will contribute greatly to the Army's ability to fight outnumbered --- and win!

Recently, there have been numerous articles and reports addressing the problems associated with high complex and sophisticated weapon systems that exceeded their performance requirements but became operating and maintenance nightmares when they were fielded. While the statistics vary from study to study the basic problems reported were similar in nature: (1) Excessive maintenance downtime; (2) Excessive removal and replacement of good hardware; and (3) Equipment design too complex for available maintenance skill levels. To preclude these problems on the Advanced Attack Helicopter, both Hughes and the Army have stressed reliability and maintainability requirements as basic drivers throughout the design effort.

This emphasis on reducing reliability and maintainability problems from those experienced on earlier weapon systems brought about many specific design features in the AH-64: transmission and engine removal without removing the rotor head; low-vibration rotor system; integral work platforms; excellent access to electronic, visionics and avionics equipments; and an innovative Fault Detection/Location System (FD/LS). This paper will cover the AH-64 FD/LS. The FD/LS objectives, requirements, development techniques and problems, equipment design and operating procedures, and the role of the "Man-in-the-Loop will all be addressed.

The primary objectives of the AH-64 Fault Detection and Location System were to: (1) Avoid flying the aircraft with failed mission essential or flight critical hardware; (2) Minimize maintenance down time; and (3) Prevent the removal and replacement of good hardware. Other related objectives were for the FD/LS system itself to be cost-effective, easy to operate and easy to maintain.

The overall AH-64 Fault Detection/Location System is defined by the Government as an optimum mix of Built-in Test Equipment (BITE), onboard diagnostic equipment, ground test equipment, automatic test equipment, technical manuals, diagnostic procedures, and other design techniques. A thorough analyses of AH-64 mission requirements and systems hardware, in light of FD/LS objectives to ensure that FD/LS equipment, personnel and procedures were indeed optimized, was the major challenge of this systems development effort.

RELIABILITY AND MAINTAINABILITY ANALYSES

As noted above, both Hughes Helicopters and the Army have placed special emphasis on reliability and maintainability requirements throughout the Advanced Attack Helicopter design process. While there were numerous

techniques and procedures involved in the AH-64 Reliability and Maintainability Programs, the primary elements involved in the FD/LS development effort were Reliability FMECA data and Maintainability Engineering Analyses conducted in accordance with Reliability Centered Maintenance principles.

Reliability Failure Modes, Effects, and Criticality Analysis (FMECA) reports were prepared on the total AH-64 system, major assemblies, AVUM Replaceable Units, and significant Replaceable Modules. Mission and system reliability failure modes were analyzed to the level necessary to meet the overall mission and system reliability requirements. The FMECA for each level of analysis identified the hardware, its quantity and function, all identifiable failure modes, the frequency of each failure mode and the effect of the failure mode on the subsystem and system. Failure rates and K-factors for nonstandard parts were obtained from MIL-HDKBK-217A, the GIDEP (FARADA) handbook, or from vendor data for state-of-the-art devices that have not been published in MIL-M-38510, General Specification for Microcircuits.

Maintainability Engineering analysis of the FMECA data was conducted in the development of the AH-64 Maintenance Plan. This analysis involved the application of the principles of Reliability Centered Maintenance (RCM), using the Army's DARCOM-P 750-16 Pamphlet, Appendix C as a guide. RCM provides a logic process that results in the segregation of maintenance requirements into:

(1) On-condition category: scheduled inspections or tests to measure deterioration of an item, with the item either remaining in service or corrective maintenance being performed.

(2) Hardtime category: scheduled removal tasks based on predetermined fixed intervals of age or usage.

(3) Condition monitoring category: unscheduled tasks on components which are allowed to fail or components where impending failure can be detected by crew through routine monitoring during normal operations.

In a sharp departure from the traditional approaches, RCM forces maintenance attention more on the actual condition of the equipment and less on mandatory inspections and hard time removals. The driving force in the development of maintenance planning for the Advanced Attack Helicopter was to reduce the scheduled maintenance burden and operating and support cost incurred by the system while maintaining the necessary readiness rate.

RCM logic was applied to each replaceable unit in the system, addressing each individual failure mode. The RCM logic presented in DARCOM-P 750-16, Appendix C, is structured into block diagrams which logically addresses such factors as mission/flight criticality, rate of and detectibility of degradation of the item, cost impact associated with

scheduled and unscheduled maintenance, and criteria for categorizing the maintenance task. The criteria upon which this logic process is based is that: (1) Scheduled maintenance tasks should be performed on non-critical components only when such scheduled tasks reduce the life cycle cost of the system; and (2) scheduled maintenance tasks should be performed on critical components only when such tasks will prevent deterioration in reliability and/or safety to unacceptable levels, or when such tasks reduce life cycle costs.

There were no hard-time limits established on AH-64 components as a result of this analysis process. All scheduled inspections and tests on the AH-64 were categorized into on-condition limits, which are included in Phased-Maintenance procedures. Some components were included in both the condition monitoring category and the on-condition category, while the remaining components were categorized for condition monitoring only.

As described in DARCOM-P 750-16, Appendix C, condition monitoring is the process where the operator or crew detects either impending or experienced failures through routine monitoring of equipment operation and use. Impending failures are those detectable either directly through the human senses (vibration, heat, noise, etc.), or indirectly, through design features such as Built-in Test Equipment (BITE) and sensors/transducers (warning lights, gauges, etc.) before they occur. The experienced failures are those that are detected by the operator or crew when or after they occur.

It should be emphasized that these reliability and maintainability analysis processes were structured to generate design changes when that action was indicated by analysis results. In addition, these analyses were iterative in nature and were reapplied as measured values became available to replace predicted values, and as design changes were implemented. This ensured that reliability and maintainability requirements were part of the earliest stages of design and that they were reinforced throughout all stages of the Advanced Attack Helicopter design process. Further, reliability and maintainability performance data was recorded and analyzed throughout an extensive flight test program to ensure that the AH-64 complied with rigorous and specific reliability and maintainability requirements.

FAULT DETECTION/LOCATION SYSTEM REQUIREMENTS

The general design requirements for this system were negotiated by Hughes and the Army during the competitive phase of the Advanced Attack Helicopter program. The general requirements for the FD/LS include the capability to: (1) provide on-aircraft inflight "GO/NO-GO" status of mission essential subsystems; (2) detect failures of flight critical subsystems; (3) fault isolate electrical and electronic failures to the Aviation Unit Maintenance (AVUM) replaceable unit; and, (4) provide electrical and electronic fault isolation within removed replaceable

units. Additionally, FD/LS must be fail-safe so that its failure will not degrade the performance of monitored components.

In designing the AH-64 FD/LS Hughes Helicopter established specific requirements regarding the percentage of failures to be detected and located by FD/LS and the percentage of "false alarms" allowed. The on-aircraft fault location requirement specified that EACH AVUM electrical and electronic replaceable unit must provide for at least 95 percent of its failures, weighted by failure rate, to be indicated by the FD/LS system, with no more than 2 percent erroneous indications.

This requirement to isolate at least 95 percent of the failures in "each" replaceable unit resulted in several difficult problems. The basic problem in specifying the requirement for "each" unit stems from the wide range in reliability (MTBF) between the 137 replaceable units monitored by FD/LS. The data presented in Figure 1 shows that 47 of these replaceable units (35 percent of all units) have an MTBF greater than 20,000 hours. At a war time flying rate of 1320 hours per year the aircraft would accumulate a total of 19,800 flying hours during its 15 year service life. It can be seen from Figure 1, which was developed from the reliability FMECA reports, that it is predicted that some replaceable units will not fail within two or more lifetimes of the aircraft. (Figure 2 presents a distribution of this data showing the percentage of detectable failures within aircraft lifetimes based on a wartime flying rate of 1320 hours per year. Figure 3 shows the same type of distribution based on a peacetime flying rate of 360 hours per year.) In the case of some highly reliable mission essential or flight critical hardware, such as the Flight Control Position Sensors (100,000 hours MTBF) it is effective from a flight safety point of view to detect and locate more than 95 percent of their total failures. In other instances, involving less critical hardware, it may not be cost effective to meet this requirement. Conversely, it is also true that on some of the less reliable units 95 percent of the failures may be too low -- conventional troubleshooting for 5 percent of the failures in the range of 95 to 100 percent on one unit with low reliability may result in more maintenance downtime than such troubleshooting would entail for say 50 percent of the failures on a unit with high reliability.

An alternate approach to determine the type and quantity of failures to be detected and located would be to establish an overall requirement for the total system. Although the distributions in Figures 2 and 3 indicate that 95 percent may be unnecessarily high for the AH-64, a requirement that "the Fault Detection/Location System shall detect and locate at least 95 percent of all the failures occurring in all electrical and electronic replaceable units specified in the weapon system, with no more than 2 percent erroneous indications" could be implemented to satisfy FD/LS design objectives on an effective and efficient basis, using the reliability and maintainability analysis and tradeoff process described earlier.

MTBF	LRU QUANTITY	% OF TOTAL LRU'S
300 – 5000	41	30
5001 – 10,000	22	16
10,001 – 15,000	13	9
15,001 – 20,000	14	10
20,001 – 25,000	9	7
25,000 – 30,000	7	5
30,001 – 35,000	2	2
35,001 – 50,000	6	4
50,001 – 100,000	15	11
> 100,000	8	6
	137	

Figure 1: MTBF Distribution by Number of LRUs

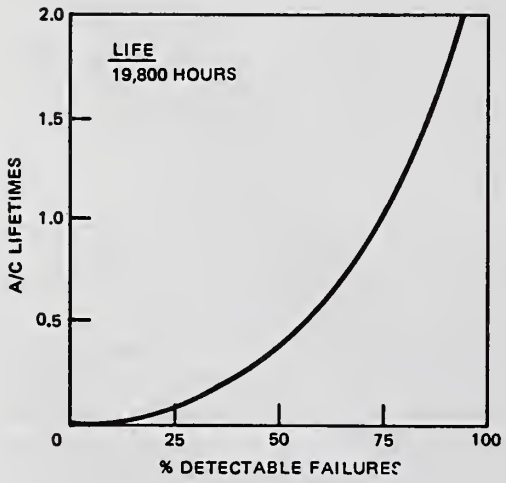


Figure 2: % Detectable Failures by A/C Lifetime (1320 hours per year)

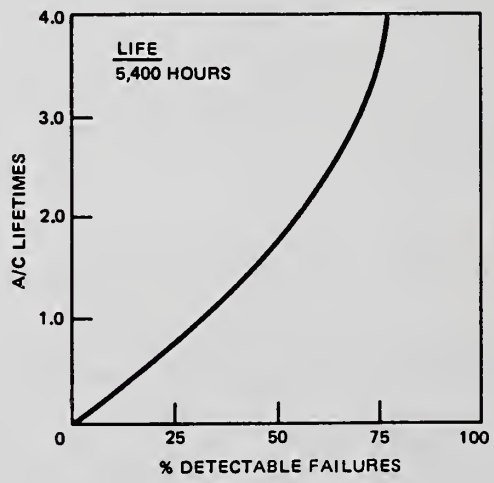


Figure 3: % Detectable Failures by A/C Lifetime (360 hours per year)

FAULT DETECTION/LOCATION SYSTEM DESIGN

Notwithstanding the foregoing, Hughes Helicopters has been very successful during the Full Scale Engineering Development Phase of the AH-64 Program in meeting both the objectives and requirements of the FD/LS. The current FD/LS design will detect and locate at least 95 percent of all the failures expected to occur on each of 104 replaceable units. Further, the current design will detect and locate over 91 percent of all the failures expected to occur on all the replaceable units included in the FD/LS system. Follow-on design improvements have already been developed to ensure that the production aircraft FD/LS has sufficient test provisions so that at least 95 percent of all failures within each replaceable unit result in a failure indication.

The overall AH-64 FD/LS is an optimum mix of design features such as Caution and Warning Lights, computer-oriented BITE, Ground Test Equipment and Automatic Test Equipment coupled with Man-in-the-Loop, Technical Manuals and Diagnostic Procedures.

Caution and Warning System

A major portion of the overall AH-64 FD/LS is included in the Caution and Warning System. The caution and warning system provides visual indications of systems status and visual and aural indications of actual and impending failures critical to aircraft mission or flight safety. Various devices, such as chip detectors, pressure sensors, temperature sensors and valve or switch position indicators are included in equipment designs throughout the aircraft and are interconnected with caution and warning equipment installed in the crew stations.

Master Caution and Warning Panels and Caution, Warning and Advisory Panels (Figures 4 and 5) are installed in both the pilot and copilot/gunner stations. The two Master Caution and Warning Panels, one located on the top center of the pilot's instrument panel and the other on the top right side of the copilot/gunner's instrument panel, provide the initial indications of impending failure, actual failures, or dangerous conditions. The MASTER CAUTION display on these Master Caution and Warning Panels is pushbutton operated. Initially, the MASTER CAUTION will flash (5 ±1 hertz rate) when a Caution, Warning and Advisory Panel segment simultaneously starts flashing (2 ±1 hertz rate). Pressing the MASTER CAUTION display will cause it to extinguish and will convert the flashing fault segment to steady on. It will remain on until the fault or condition is corrected. When the PRESS TO TEST button on the Master Caution and Warning Panel is pressed, all Caution, Warning and Advisory lights in the crewstation are illuminated. When any of the remaining warning lights on the Master Caution and Warning Panel are lit, immediate attention is required by the crew members in accordance with operating instructions. An aural tone (700 to 1000 hertz continuous sweep) is incorporated with the LOW RPM ROTOR, ENG 1 OUT and ENG 2 OUT segments

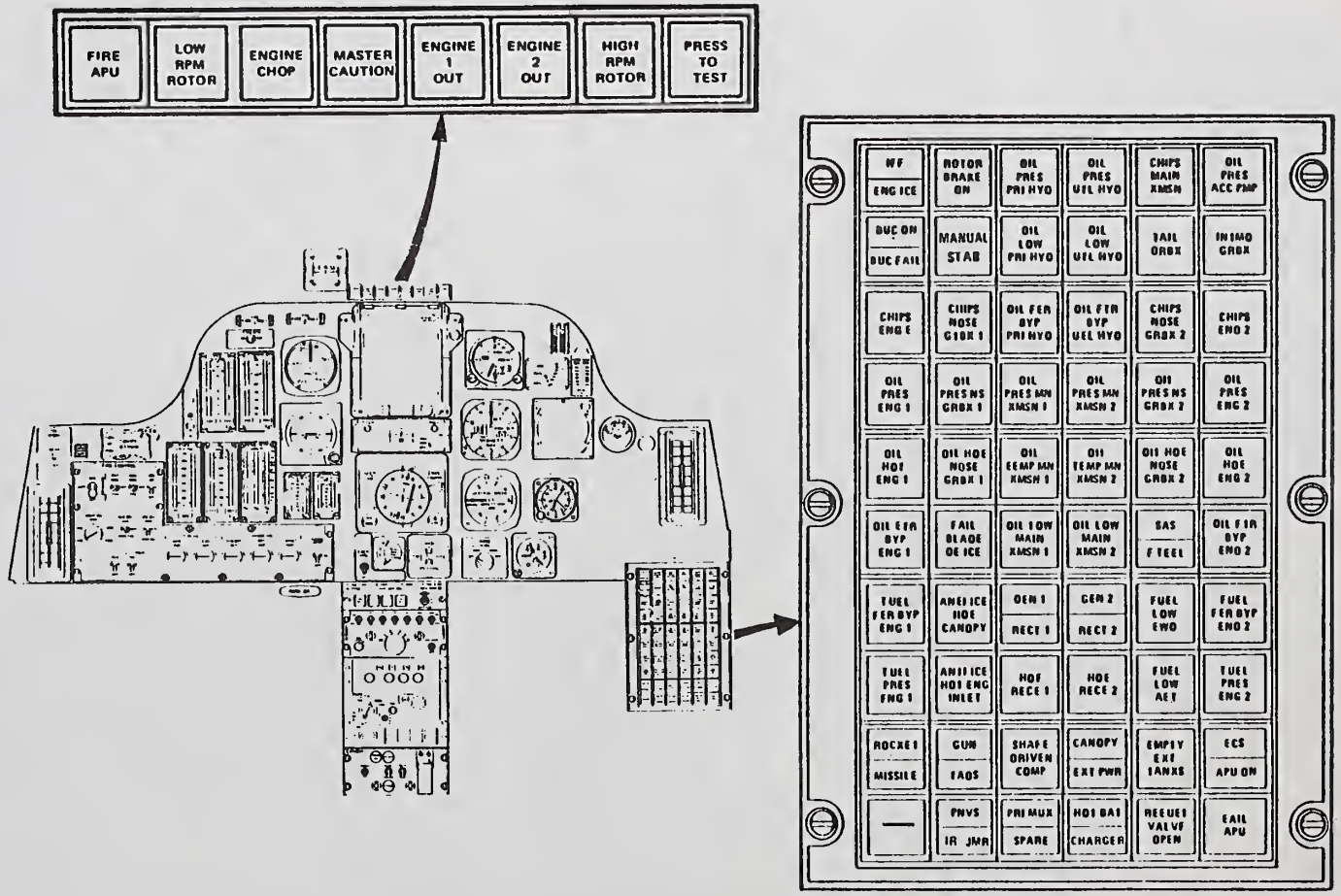


Figure 4: Pilot's Master Caution and Warning/Caution, Warning and Advisory Panels

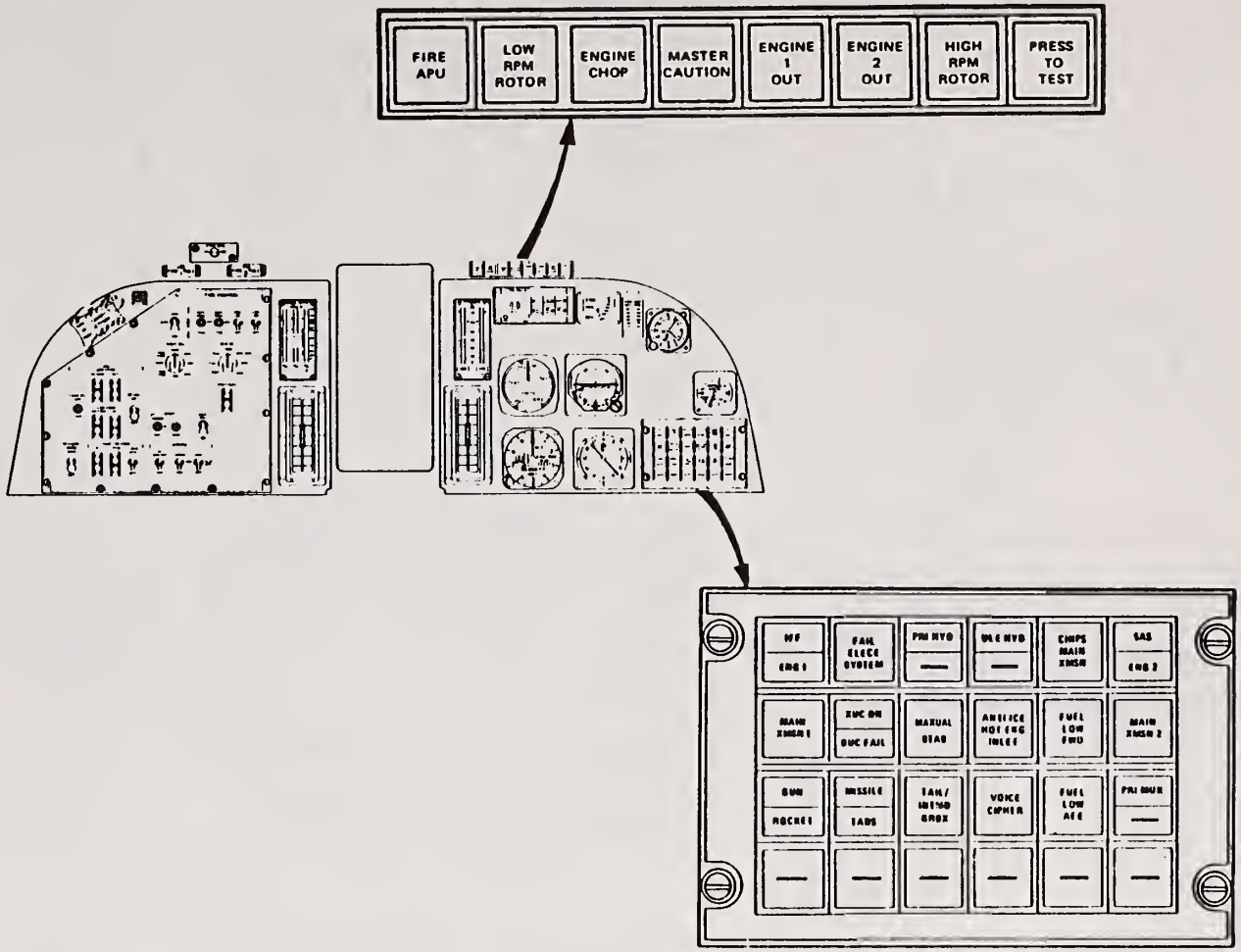


Figure 5: Copilot/Gunners Master Caution and Warning Panel/Caution and Advisory Panels

on the Master Caution and Warning Panels. The MANUAL STAB segment on both Caution, Warning and Advisory panels incorporate a steady 1000 Hz aural tone.

Other caution, warning and advisory indicators are located with associated subsystem panels installed in the crew stations. In addition, there are appropriate gauges, indicators and instruments in the pilot and copilot/gunner instrument panel which serve as system status and caution/warning advisors.

FD/LS on Multiplex System

This portion of the overall AH-64 FD/LS is included as part of the Multiplex (MUX) and Fire Control Computer, (FCC) subsystems. The AH-64 Multiplex system is a general purpose information transfer system that performs the function of command and control of avionic and mission equipment functions, and provides for FD/LS signal routing and processing. Conforming to MIL-STD-1553B, the AH-64 Multiplex system makes this the first helicopter to incorporate a multiplex data bus system for subsystem interface and data handling.

The FD/LS operation of this system provides CONTINUOUS in-flight monitoring of electrical/electronic mission essential and flight critical systems for "GO/NO-GO" status, with in-flight/on the ground ON-DEMAND monitoring by the copilot/gunner or ground maintenace personnel. The FD/LS detects and locates failed AVUM electrical/electronic replaceable units, with equipment status annotated on the Caution and Warning panels or displayed on the TADS Heads Out Display (HOD) and Heads Down Display (HDD). This FD/LS capability is provided through operation of the Multiplex (MUX) data bus software programs in the Fire Control Computer, a Data Entry Keyboard, Symbol Generator, Caution and Warning Panels, TADS Displays, and the fault sensor or BITE of the subsystems being monitored. Figure 6 shows the AH-64 Multiplex system distribution throughout the aircraft, highlighting widely separated redundant data buses and bus controllers (primary residing in the FCC; backup residing in the copilot compartment Remote Terminal Unit Backup Bus Controller BBC) for improved reliability and survivability. An overview of the FD/LS functions of this equipment is summarized below:

Data Bus Operation. The AH-64 MUX data buses consist of low-loss twisted, shielded, 24 gauge, Teflon insulated wire pairs, terminated at each end for impedance matching. The data bus operates asynchronously in a command/response mode, with data transfer occurring in either direction, but only one direction at a time (half duplex). All connections to the data bus system use a Data Link Terminal Unit (DLTU) which provides short-circuit isolation, impedance matching, and line termination. Sole control of data transfer on the bus resides with the bus

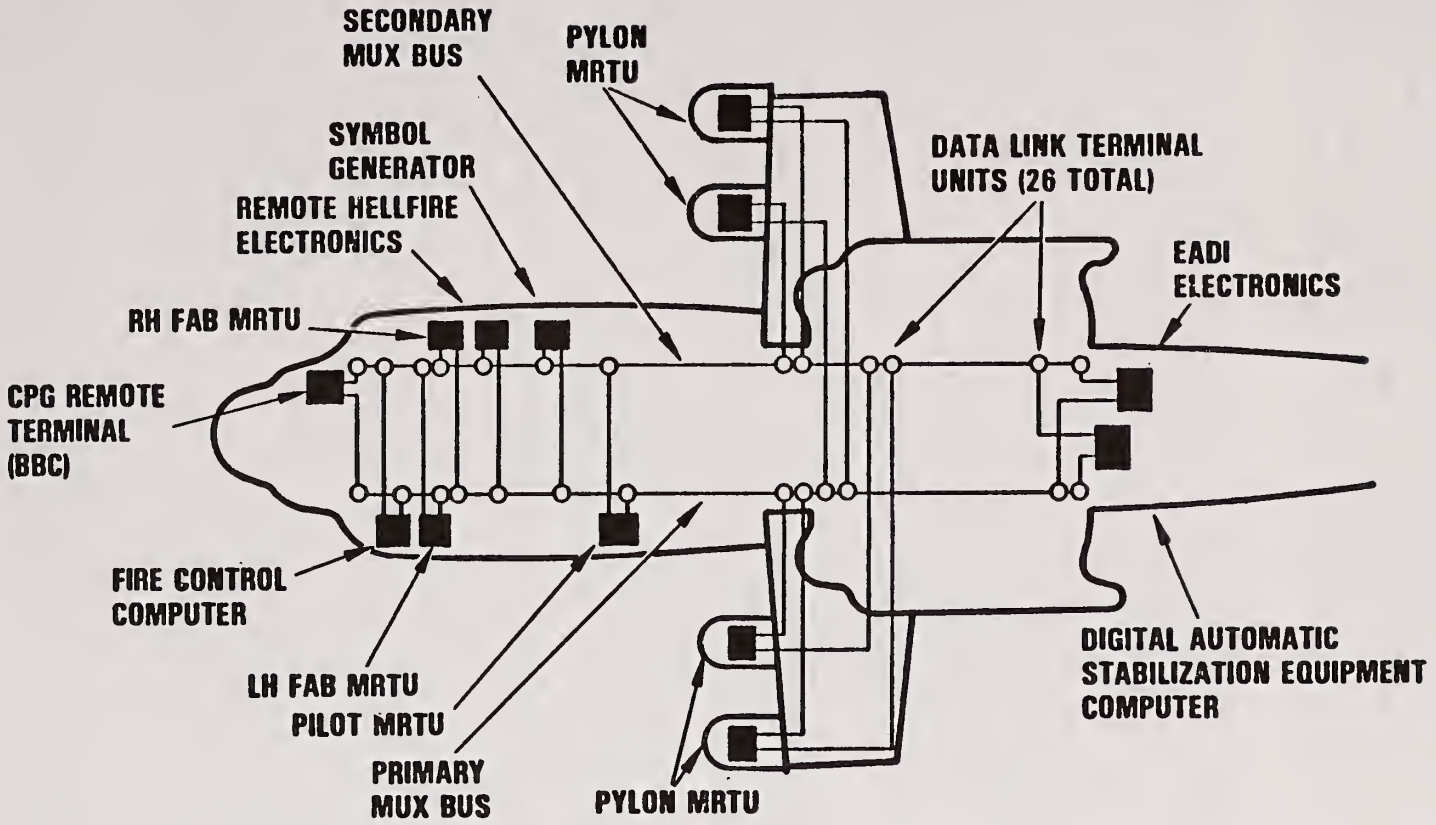


Figure 6: AH-64 Multiplex System Distribution

controller (FCC primary; BBC secondary) which initiates all data (both analog and digital) transmissions. Time Division Multiplexing (TDM) allows transmission of signals to more than one unit over one data bus line by staggering the time sequence of the signal. Data bus main frame time is a nominal 20 milliseconds (50 times per second) while functions not requiring this high of an update rate are processed at lower rates of 25 times per second, 12-1/2 times per second, 6-1/4 times per second, or 3-1/8 times per second.

Fire Control Computer (FCC). The FCC is the primary computer for FD/LS functions, with logic processing capabilities sufficient to perform sequencing, interlock priorities and interrupts, and other control functions involving the discrete, analog, and digital signals associated with the AH-64 MUX system. The FCC contains software programs for data entry, continuous monitoring routine, end-to-end test routine, and individual test routines to provide the required control flexibility. As indicated earlier, the FCC interfaces with the systems under test as well as other FD/LS components through the MUX system. The FCC meets the fail-safe operational requirements of MIL-STD-1553B, and performs continuous self-test functions to determine failures and accomplish transfers to redundant components, circuits, or modes of operation.

Multiplex Remote Terminal Units (MRTU). The MRTUs provide interface between the MUX system and the aircraft systems being monitored. There are three standard aircraft MRTUs used in the AH-64 data bus system. The remote terminal units input and output a standard assortment of bilevels, ac and dc analog, serial digital, and synchro input/output signals to the aircraft systems. These remote terminal units contain redundant data bus interfaces, and they contain sufficient built-in circuitry to detect 95 percent of all faults within each MRTU.

Back-up Bus Controller (BBC). The BBC is a computer within an MRTU located in the copilot/gunner's station. The BBC automatically assumes control of the FD/LS if the FCC fails, or if a manual switch located in the copilot/gunner's Fire Control Panel is placed in an override position. The BBC contains the capability to perform the FD/LS continuous monitoring routine and the associated display routines.

Data Entry Keyboard. The Data Entry Keyboard is located in the copilot/gunner's station and provides the means for the copilot/gunner or maintenance personnel to enter FD/LS test modes and to acknowledge actions taken. When a manual switch in the keyboard circuit is so positioned, the data entry keyboard provides itself with continuous internal self testing.

Symbol Generator. The AH-64 Symbol Generator takes information from the interfacing subsystems equipment and generates the necessary character symbology information. This information provides FD/LS status data visually displayed on TADS Heads Out and Heads Down Display Units. The Symbology Generator also contains a BITE self-test capability.

Target Acquisition and Designation Sight (TADS) Displays. The TADS provides three displays capable of presenting FD/LS messages: Heads Out Display (HOD), Heads Down Display, and the Alphanumeric Display (AND). The displayed messages announce test progress, required operator action items, and status information. As indicated above, the messages to be displayed on the HOD and HDD are generated by the Symbol Generator. The messages to be displayed on the AND are generated and commanded by the FCC.

FD/LS BITE. There are two categories of FD/LS BITE included in this system: (1) Equipment that has a microprocessor (computer) as part of its BITE; and (2) Equipment without a microprocessor. With equipment that has a microprocessor controlling BITE, the self-test is initiated by a signal sent from the bus controller via the MUX bus to the microprocessor. The microprocessor then runs the BITE and sends the resulting test data, via the MUX bus, back to the bus controller. Each bit, or bit pattern in this test data, corresponds to either the GO/NO GO status of the equipment as a whole, or individual functions, or AVUM replaceable units. Appropriate FD/LS software then checks for and displays any failures. With equipment that does not have a microprocessor to run the BITE, the parameters of the equipment are transmitted to the bus controller, in COMMAND/RESPONSE mode, over the MUX bus. The data (equipment parameters) is then evaluated by FD/LS software in the bus controller to detect any abnormalities in the operation of the equipment. If a significant abnormality (failure) is detected, the software will isolate the problem to the appropriate AVUM replaceable unit, and announce it to the crew.

As previously indicated, the FD/LS functions integrated with the MUX bus are designed to handle continuous monitoring of mission essential and flight critical equipment and keyboard initiated equipment monitoring. Figure 7 is presented to show an overview of these FD/LS interactive system devices.

With the continuous monitoring FD/LS capability most equipment will run a continuous self-check at a functional level without assessing detailed parameters. These equipments generally check critical components or functions such as a processor, power supply or critical timing. If any of these components or functions show an abnormality (failure), an appropriate signal is sent to the computer controlling the data bus. This data transmission will then result in the Caution and Warning Panel announcing the failure; or the copilot/gunner getting a failure indication on one of the TADS displays. If the crew then requires additional information about the type of failure or what capability has been lost, the copilot/gunner will initiate the appropriate FD/LS test for that equipment through the Data Entry Keyboard Panel. The following mission essential or flight critical equipment is under continuous FD/LS monitoring:

- POINT TARGET
- AREA WEAPON

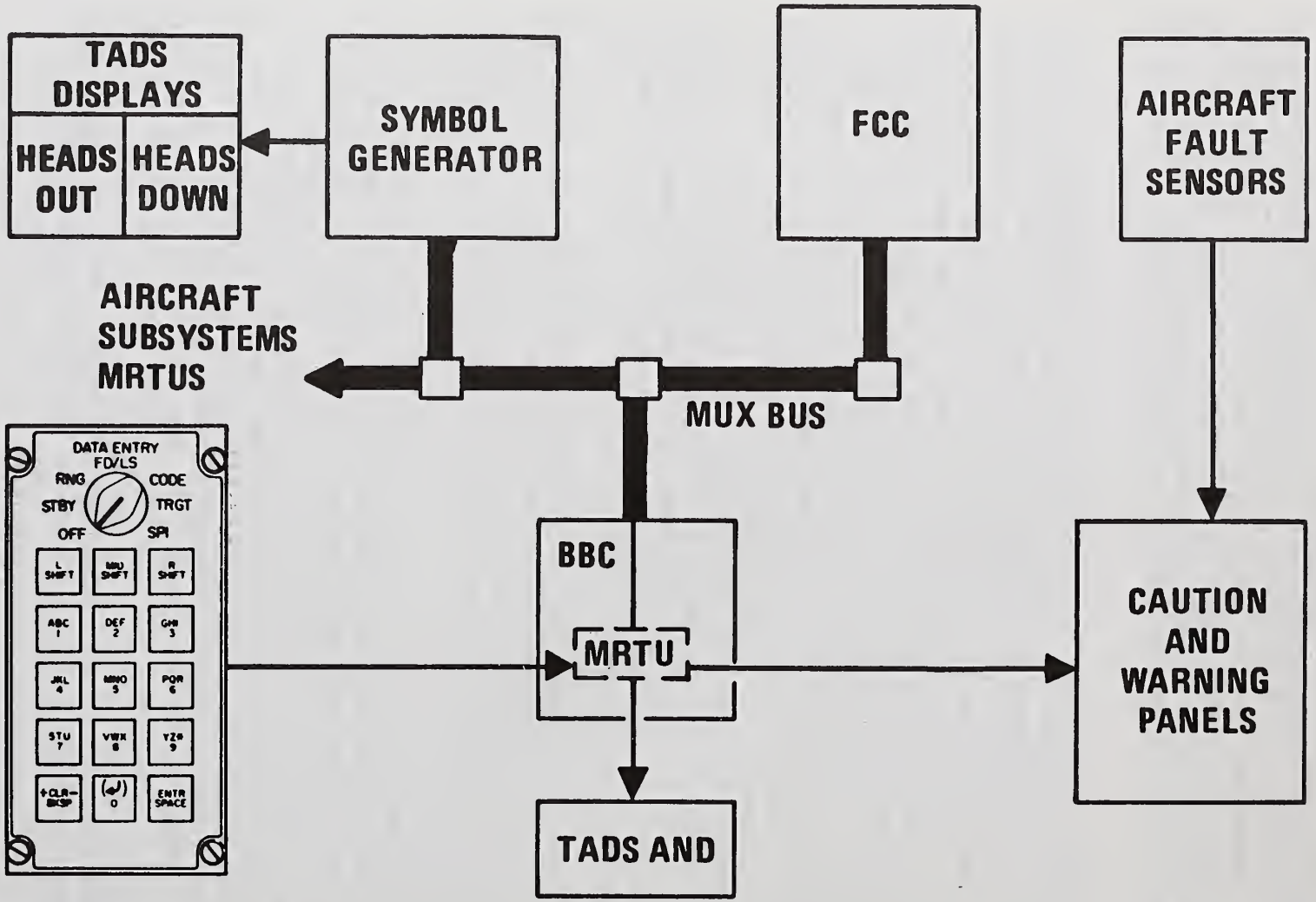


Figure 7: FD/LS Interactive System Devices

- AERIAL ROCKET
- EXTERNAL STORES
- TADS/PNVS
- DIGITAL AUTOMATIC STABILIZATION EQUIPMENT (DASE)
- ELECTRONIC ATTITUDE DISPLAY INDICATOR (EADI)
- DATA ENTRY KEYBOARD
- AIR DATA SYSTEM
- HEADING ATTITUDE REFERENCE SYSTEM (HARS)
- INTEGRATED HELMET AND DISPLAY SIGHT SYSTEM (IHADSS)
- MULTIPLEX
- SYMBOL GENERATOR

When a FD/LS test is initiated via the keyboard, the code for the requested test is preceded by either a "G" (for copilot/gunner) or an "M" (for maintenance personnel). The major difference in these data entries is reflected in the displays. When a test code is preceded by a "G" and a failure has occurred in monitored equipment, the display will indicate system status, such as EADI NO-GO. When a test code is preceded by an "M" and a failure has occurred in monitored equipment, the display will indicate an AVUM replaceable unit status, such as EADI Display Unit NO-GO Pilot Comp. (Figure 8 lists the systems/ equipment monitored by keyboard initiated test and the Keyboard Entry Codes.)

Man-in-the-Loop FD/LS

As stated earlier, the aircrew and maintenance personnel, as well as the Technical Manuals and Diagnostic Procedures, are also part of the AH-64 FD/LS. When faults or failures can be effectively detected and located by human observation, then FD/LS design features are not added to the related equipment design. An example of this FD/LS Man-in-the-Loop capability would be the communications equipment.

In other Man-in-the-Loop actions, the flight crew or ground maintenance personnel must make observations and/or perform operations during FD/LS on-demand test operations and acknowledge observation results or actions through the Data Entry Keyboard. The FD/LS program will then execute the next step or sequence of steps in the test and display the results, and display additional actions or inquiries of the Man-in-the-Loop. For example, when the in-flight continuous monitoring procedure indicates a failure in the DASE by Displaying "DASE NO GO", the ground maintenance personnel would operate the FD/LS and interface with the systems as follows:

MAN-IN-LOOP: "MDASE"

FD/LS DISPLAY: "ENGAGE ROTOR BRAKE"

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "CENTER ALL CONTROLS AND ENGAGE FORCE TRIM."

SYSTEM TEST	KEYBOARD ENTRY CODE
END-TO-END TEST	G/M ETE
MULTIPLEX SYSTEM	G/M MUX
PILOT NIGHT VISION SENSOR	G/M PNVS
SYMBOL GENERATOR	G/M SYGN
TARGET ACQUISITION AND DESIGNATION SIGHT	G/M TADS
ELECTRICAL GENERATION	G/M EGN
MAIN TRANSMISSION/NOSE GEARBOX	G/M TRAN
AIR DATA SUBSYSTEM	G/M ADS
ICE DETECTOR	G/M ICED
ROTOR BLADE ANTI-ICE	G/M RBD
CANOPY ANTI-ICE	G/M CTC
EXTERNAL STORES	G/M EXST
HEADING ATTITUDE REFERENCE SYSTEM	G/M HARS
ELECTRONIC ATTITUDE DISPLAY INDICATION	G/M EADI
INTEGRATED HELMET AND DISPLAY SIGHT SYSTEM	G/M IHDS
AERIAL ROCKET CONTROL SYSTEM	G/M ARCS
HELLFIRE MISSILE SYSTEM	G/M MSL
AREA WEAPON	G/M GUN
APU CONTROLLER	G/M APU
STABILATOR	G/M STAB
DATA ENTRY KEYBOARD	G/M DEK
DIGITAL AUTOMATIC STABILIZATION EQUIPMENT	G/M DASE

Figure 8: On Demand System Tests and Keyboard Entry Codes

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "CHECK FOR FREE CYCLIC, PEDAL AND COLLECTIVE MOVEMENT."

MAN-IN-LOOP: PERFORM CHECK AND RESPOND "YES" or "NO" VIA KEYBOARD

FD/LS DISPLAY (IF NO): "CAN NOT RUN DASE FD/LS. PERFORM CORRECTIVE ACTION."

FD/LS DISPLAY (IF YES): "ENGAGE PITCH AND ROLL SWS ON DASE PANEL."

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "IS BUC ON? C & W LIGHT ON AND SAS AND BUC FAIL C & W LIGHT OFF?"

MAN-IN-LOOP: PERFORM CHECK AND RESPOND "YES" OR "NO" VIA KEYBOARD

FD/LS DISPLAY: "ENGAGE ALL DASE PANEL SWS. CYCLE BUCS S/T SW TO PLT CPG. CENTER POS."

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "PLT TOGGEL FORCE TRIM SW TO OFF, ON, MOM REL. PRESS DASE RELEASE SW."

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "ARE SAS AND BUC FAIL C & W LIGHTS ON, BUC ON C & W LIGHTS OFF?"

MAN-IN-LOOP: PERFORM CHECK AND RESPOND "YES" OR "NO"

FD/LS DISPLAY: "ENGAGE ALL ASE PANEL SWS. CPG PULL BUCS LVDT SEL TRIGGER. PRESS TRIM & ASE RELEASE SWS."

MAN-IN-LOOP: PERFORM TASKS AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: "IS TURN RATE INDICATOR ON EADI APPROX HALF SCALE ON RIGHT?"

MAN-IN-LOOP: PERFORM CHECK AND RESPOND "YES" OR "NO" VIA KEYBOARD

FD/LS DISPLAY: "ENGAGE PITCH SAS SW."

MAN-IN-LOOP: PERFORM TASK AND ACKNOWLEDGE VIA KEYBOARD

FD/LS DISPLAY: PERFORMS CHECK OF ALL REPLACEABLE UNITS AND DISPLAYS ALL FAILED UNITS IN DASE

It should also be noted that the Maintenance Procedures and Manuals developed for the AH-64 are in compliance with the content and format requirements of Skill Performance Aids (SPA) Figure 9. These SPA manuals, coupled with the FD/LS design features described earlier ensure that the FD/LS can be operated and maintained with maintenance skill levels currently available in the field.

AVIM and Depot Automatic Test Equipment

Another important segment of the overall AH-64 FD/LS is the Automatic Test Equipment (ATE) for AVIM and depot level testing of all avionics, electronics and visionics equipment. The AH-64 ATE was developed by RCA Automated Systems, with extensive "team support" provided by Hughes Helicopters and the Army and the other aerospace companies involved in the Advanced Attack Helicopter Program as Associate Contractors and Subcontractors. This team effort provided extensive information reflecting the combined points of view of the user, the weapon systems integrator and the designer and manufacturer of the equipments to be tested.

The requirements developed for the ATE segment of the FD/LS included testing capability so that at least 98 percent of all failures weighted by failure rate could be detected and located to the repairable module fault, with no more than 2 percent erroneous indications. Further requirements specified: (1) That failure isolation of the replaceable units must be accomplished without disassembly of the unit or removal of covers; (2) That substitution of known good replaceable modules, or probing as a means of fault isolation is not allowed; and, (3) That calibration or adjustment of the replaceable units would not be required when they were installed in the next higher assemblies.

RCA, in conjunction with Hughes Helicopters and the other AH-64 team members, developed FMECA's, Optimum Repair Level Analyses (ORLS's), and related data, along with new design approaches based on "lessons learned" from earlier ATE development programs, to ensure that the AH-64 ATE complied with system requirements. The resulting AH-64 ATE is a third generation system using its computer to generate stimulus signals and to perform diagnostics and fault location, as well as to control the testing procedure. The system eliminates racks of special test devices, simplifies test procedures, and provides the flexibility necessary to support the diverse subsystem equipment of the AH-64 helicopter.

SUMMARY

The primary objectives of the AH-64 FD/LS were to: (1) Avoid flying the aircraft with failed mission essential or flight critical hardware; (2) Minimize maintenance downtime; and (3) Prevent the removal and replacement of good hardware. Each of these objectives represent major problem areas experienced in earlier programs involving complex high performance weapons systems, and it was recognized that an effective

TASK STATEMENT: FD/LS On Aircraft Monitor System Test Caoopy Anti-Ica Subsystem	PREPARED BY: J. Thompson	DATE: 1 May 80	REVISION: 0	DESTINATION	1 OF 4	OC	FGC/TASK CODE: 7121(B)/OC 0

STEP	PROCEDURE	RESULT	FOLLOW-UP ACTION	ILLUSTRATION
A	PRELIMINARY TASKS.			
1	Perform FD/LS On-Aircraft Monitor System Tast Preliminary Operation Set Up (FGC FD/LS).		Go to B. PROCEDURAL TASKS.	
B	PROCEDURAL TASKS.			
1	Oo pilots ovarhead circuit breakar panal, close circuit breakars: a. CANOPY ANTI ICE CONT (1). b. CANOPY ANTI ICE (2).		Go to Step 2.	
2	On pilots ANTI-ICE panel, aet HTR CANOPY switch (3) to ON.		Go to Stap 3.	

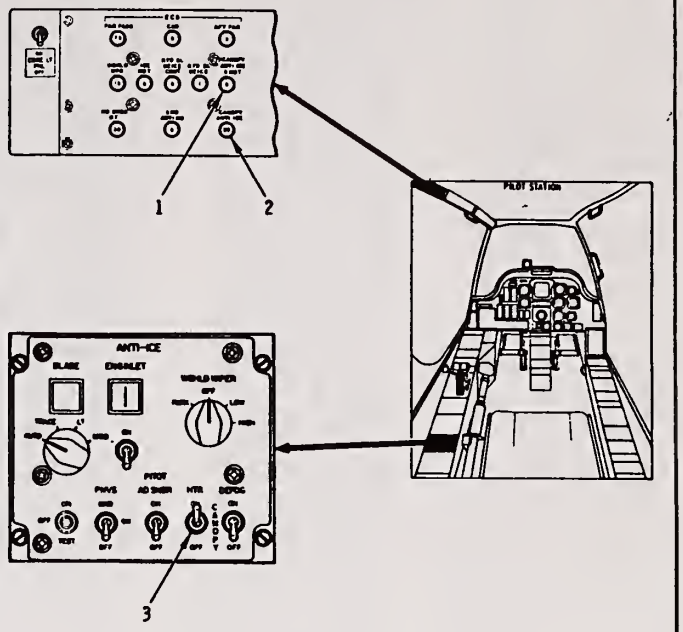


Figure 9: SPA Maintenance Manual

Fault Detection and Location System would significantly reduce these problems. The need for good reliability and maintainability features as inherent design characteristics was stressed during the earliest stages of the AH-64 design process, as was the need for ongoing testing to ensure compliance with these requirements. Emphasis was also placed on the need to base maintenance actions on the actual condition of the hardware rather than on calendar time or flying hours. Finally, requirements were established to ensure that the FD/LS equipment itself was simple to operate and maintain, and the need for an optimum mix of FD/LS hardware, technical procedures and Man-in-the-Loop operations was established and enforced.

The resulting AH-64 FD/LS design includes conventional on-board sensors and detectors interconnected with aural and visual caution and warning devices; a computer controlled multiplexing system using existing aircraft electronics and visionics equipment in conjunction with BITE for continuous and on-demand systems monitoring; and SPA, technical and maintenance manuals for simple, highly illustrated FD/LS operating and diagnostic procedures.

The six AH-64 helicopters manufactured to date have accumulated approximately 4000 flight hours and 1000 ground hours, making this aircraft one of the most thoroughly tested developmental aircraft programs in aviation history. However, the final assessment of the AH-64 FD/LS effectiveness must wait until the production aircraft is fully fielded. But developmental testing to date, including on the ground FD/LS operation by Army Maintenance personnel, clearly indicates that the AH-64 FD/LS system is an "Innovation for Maintenance Technology Improvement."

SESSION IV

IMPROVED MAINTENANCE PROCESSES

CHAIRMAN: GEORGE KITCHEN
BELL TELEPHONE LABORATORIES, INC.

SERVICE LIFE OF BEARINGS CAN BE INCREASED WITH "PROPER MAINTENANCE"

R. A. Guyer, Jr.
SKF Industries, Inc.
1100 First Avenue
King of Prussia, Pennsylvania 19406

Abstract: Many times a bearing sees only 10 to 20 percent of its calculated life due to such life shortening factors as: poor shaft and housing fits; improper installation; inadequate lubrication; dirt and water intrusion. When a bearing failure occurs it is of primary importance to be able to determine what caused the failure in order to prevent future failures.

On many occasions a bearing will be replaced without checking the shaft and housing fits and the condition of the failed bearing and as a result still another bearing will fail because the inherent deficiency in the previous installation was not properly diagnosed.

Key words: Corrosion; dirt; dirt and water intrusion; fine cracks; fine roughening of the surface; glazed surface; inadequate lubrication; life adjustment factor; minimum viscosity; misalignment; moisture; operating temperature; poor shaft and housing fits; smearing; spalling.

When a bearing has to be replaced the shaft diameter and housing bore should be checked for size according to the specifications. There should be no nicks or gouges on the shaft, shaft shoulder, housing bore and housing shoulder.

The failed bearing should be inspected for turning on the shaft or in the housing. An examination of the raceways will determine how the bearing was running.

In order to determine what is an improper installation one has to be able to "READ" what is the normal wear pattern of a properly mounted bearing. Figures 1 to 4 show the normal load zones on a properly mounted radial ball bearing. The same load zones are visible on both tapered roller and spherical roller bearings however, they are somewhat more difficult to see.

Figure 1 shows the normal load zones with inner ring rotation. Notice the load zone on the inner ring is a full 360 degrees and centrally located, whereas the load zone on the outer ring is 150 degrees and centrally located.

Figure 2 shows the normal load zones with outer ring rotation. The load zone on the outer ring is a full 360 degrees and centrally located whereas the load zone on the inner ring is 150 degrees and centrally located.

Figure 3 shows the normal load zones with an axial load. Both inner ring and outer ring have a full 360 degree load zone on the side of the groove away from the land.

Combined thrust and radial load will produce load zones as shown in Figure 4. With combined load, the load zone on the inner ring is slightly off center and the length on the outer is greater than that produced by radial load, but not necessarily 360 degrees.

If the axial load is excessive, the load zone can actually override the lands as is shown in Figure 5. This is an abnormal load zone.

Misalignment of the housing relative to the shaft will produce abnormal load zones as seen in Figure 6. When the shaft is misaligned relative to the housing, the load zones are shown in Figure 7.

When improper fits and/or too small an internal radial clearance is used, a bearing can become internally preloaded and the load zones are shown in Figure 8.

Distorted or out-of-round housing bores can radially pinch an outer ring. Figure 9 illustrates the load zones found in a bearing when the housing bore was initially out-of-round or became out-of-round by bolting the housing to a concave or convex surface. The outer ring will show two or more load zones depending on the type of distortion.

By properly being able to identify and rectify the abnormal load zones as shown in Figures 5 through 9 repeating similar bearing failures can be eliminated.

Another common bearing failure is "Inadequate Lubrication". Simply put, "Inadequate Lubrication" means that the oil if oil lubricated, or the oil in the grease if grease lubricated is not of sufficient viscosity to separate the rolling elements from the raceways.

The first stage in "Inadequate Lubrication" is a fine roughening of the surface as seen in Figure 10. The next step is fine cracks shown in Figure 11. Finally, spalling commences as shown in Figure 12 and then more advanced spalling as shown in Figure 13.

Sometimes "Inadequate Lubrication" initially manifests itself as a highly glazed or glossy surface which as damage progresses takes on a frosty appearance and eventually spalls. The highly glazed surface is seen on the roller in Figure 14.

Another form of surface damage due to "Inadequate Lubrication" is called smearing. It appears when two surfaces slide and the lubricant cannot prevent adhesion of the surfaces. This can be seen in Figure 15.

In order to obtain the proper viscosity of the lubricant it is only necessary to know the mean diameter of the bearing [(O.D. + I.D.)÷2] and the speed in RPM. From Figure 16 the minimum viscosity at the "OPERATING TEMPERATURE" can be easily obtained.

The life adjustment factor (a_{23}) can be obtained from Figure 17. There are two bands shown in Figure 17; one is for vacuum melted steels and one is for standard bearing steels. The type of bearing and the viscosity ratio v/v_1 determines the life adjustment factor (a_{23}). The upper boundary in each band is for ball and cylindrical roller bearings and the lower boundary is for spherical and tapered roller bearings.

Examples of how to use these graphs are given below:

EXAMPLE I

An SKF 6209 ball bearing is required to operate under a radial load of 395 pounds at a speed of 2000 rpm. What is the adjusted rating life? Lubrication is by static oil having a viscosity of 35 mm^2/s (165 SUS) at the bearing operating temperature.

From the catalog, the basic load rating (C) is 5700 pounds. The basic rating life is:

$$L_{10} = \left(\frac{5700}{395}\right)^3 \times 10^6 = 3000 \times 10^6 \text{ revolutions or}$$

$$\frac{3000 \times 10^6}{60 \times 2000} = 25{,}000 \text{ hrs.}$$

The minimum lubricant viscosity is obtained from Figure 16. The pitch diameter of bearing 6209 is taken as the mean between the bore and O.D. and is equal to 65 mm. At the speed of 2000 rpm, the minimum required viscosity is 13 mm^2/s (70 SUS). The viscosity ratio is therefore: $v/v_1 = 35/13 = 2.7$.

The reliability factor a_1 for 90% reliability is 1.0. The lubricant and material factor a_{23} is obtained from Figure 17 and is found to be 3 for SKF standard steels.

The adjusted rating life is:

$$L_{10_a} = a_{23} (L_{10}) = 3 \times 25{,}000 \text{ hrs.} = 75{,}000 \text{ hrs.}$$

EXAMPLE II

An SKF 22328 CJ spherical roller radial bearing is required to operate under a radial load of 32,300 pounds at a speed of 500 rpm. What is the adjusted rating life? Lubrication is by static oil having a viscosity of 35 mm^2/s (165 SUS) at the bearing operating temperature.

From the catalog, the basic load rating (C) is 220,000 pounds. The basic rating life is:

$$L_{10} = \left(\frac{220{,}000}{32{,}300}\right)^{\frac{10}{3}} \times 10^6 = 600 \times 10^6 \text{ revolutions or}$$

$$\frac{600 \times 10^6}{60 \times 500} = 20{,}000 \text{ hrs.}$$

The minimum lubricant viscosity is obtained from Figure 16. The pitch diameter of bearing 22328 is taken as the mean between the bore and O.D. and is equal to 220 mm. At the speed of 500 rpm, the minimum required viscosity is 16 mm^2/s (80 SUS). The viscosity ratio is therefore: $v/v_1 = 35/16 = 2.2$.

The reliability factor a_1 for 90% reliability is 1.0. The lubricant and material factor a_{23} is obtained from Figure 17 and is found to be 1.7 for SKF standard steels.

The adjusted rating life is:

$$L_{10_a} = a_{23} (L_{10}) = 1.7 \times 20{,}000 \text{ hrs.} = 34{,}000 \text{ hrs.}$$

The effect of dirt and abrasive in the bearing during operation will result in a gross change in bearing internal geometry. Figure 18 shows this condition.

When moisture or actual water enters a bearing it mixes with the lubricant and forms an acid which results in either static corrosion when the bearing is not turning, Figure 19, or with an overall corrosive attack on the bearing parts as shown in Figure 20.

SUMMARY

In order to achieve the calculated catalog life of a bearing for a given load, the bearing should have: (1) correct shaft and housing fits; (2) proper installation; (3) adequate lubrication; (4) free of dirt and water intrusion.

It is even possible to obtain more than the calculated catalog life by increasing the viscosity of the oil if oil lubricated, or the oil in the grease if grease lubricated in accordance with the examples previously shown. By increasing the present service life of a bearing, production will be increased resulting in a more profitable operation.

In order to help SKF's customers obtain considerably greater service life out of their bearings, SKF in 1980 introduced paid three-day "Bearing Maintenance Seminars" that are held at Corporate Headquarters in King of Prussia, Pennsylvania. Five seminars were held in 1980 and six are scheduled for 1981. Each seminar is limited to 30 persons.

The seminar highlights are shown below:

PROGRAM HIGHLIGHTS

1. Rolling Bearing Basics—Covers the fundamentals of rolling bearing technology: bearing components, loads, nomenclature, lubrication and an overview of why bearings fail.

2. Shaft and Housings—Measuring Procedures—Poor fitting practice can ruin an otherwise good bearing application in a short period of time.

3. Bearing Mounting and Dismounting Procedures—Proper mounting and dismounting procedures prevent premature bearing failure. Life shortening subjects covered are: careless handling, neglected and improper maintenance, and lubrication related failures.

4. Bearing Lubrication—Lubrication functions and principles as related to the importance of proper maintenance procedures are covered. How Heat Affects Bearings—

The higher the temperature, the more critical it becomes to select the right lubricant for an application. Learn why the wrong lubricant significantly reduces bearing life.

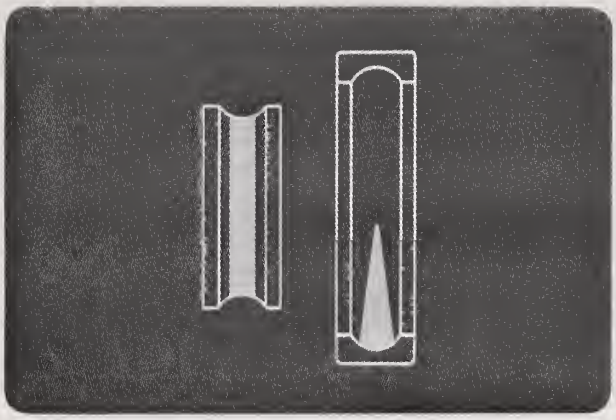
5. Bearing vibration and noise measurement.

6. Seals for bearings.

7. Interpretation of bearing failures to prevent additional failures and review of individual bearing problems.

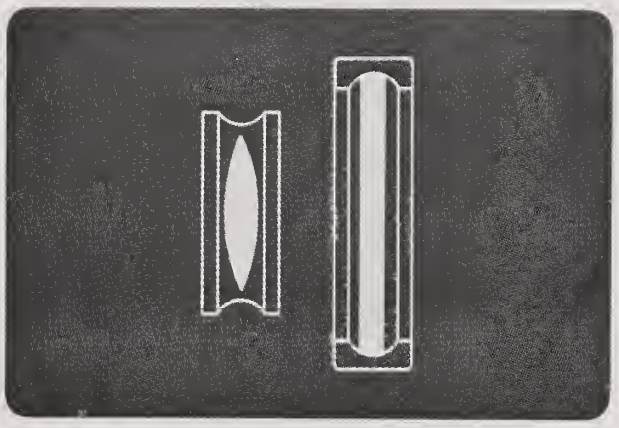
8. "Hands-on" demonstrations for mounting and dismounting bearings.

9. Tour of SKF Technology Services.



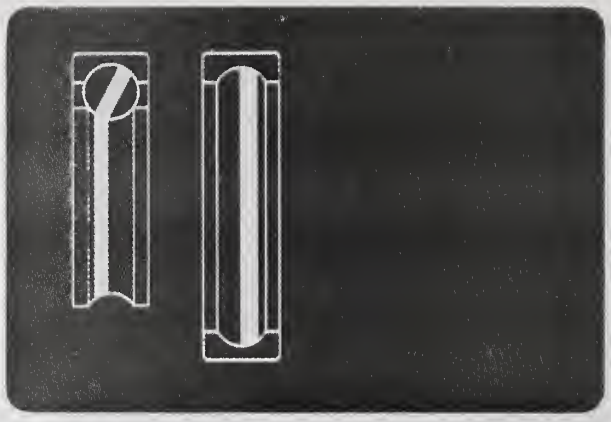
With a rotating inner ring, and a constant load direction, normal wear patterns look like this.

FIGURE 1



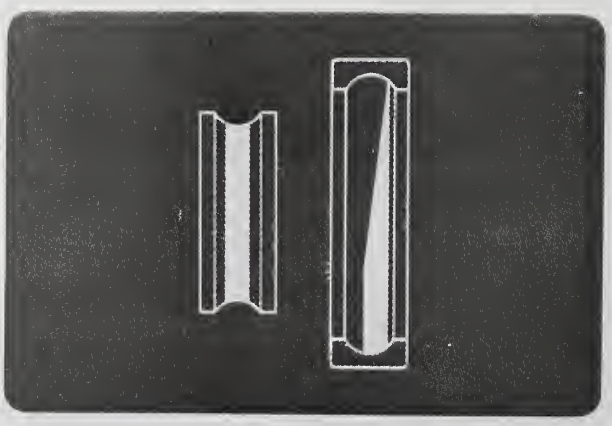
Here is a normal wear pattern where the *outer* ring rotates relative to a load of constant direction, or where the inner ring rotates and the load also rotates in phase with the shaft.

FIGURE 2



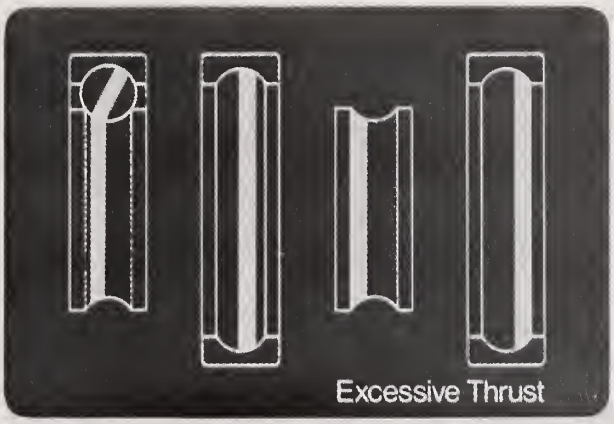
These drawings show the load zone and patterns in a deep-groove ball bearing under normal axial load.

FIGURE 3



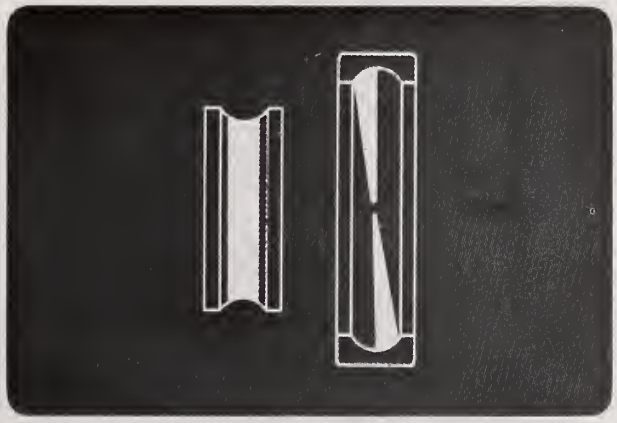
Combined thrust and radial loads will produce a normal load zone like this.

FIGURE 4



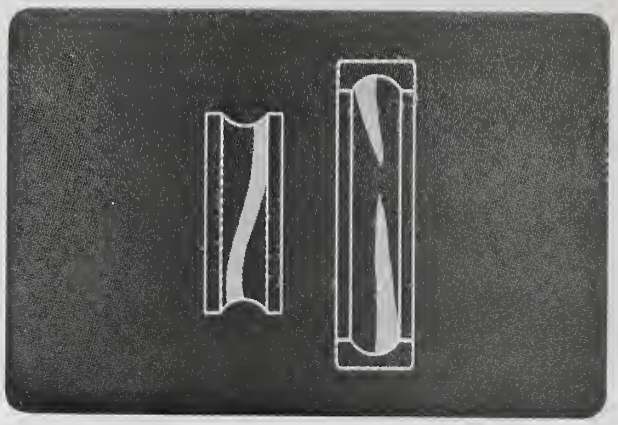
This is an example of the load path when axial loads are excessive. This is the one condition where the load paths follow the full circumference of both rings.

FIGURE 5



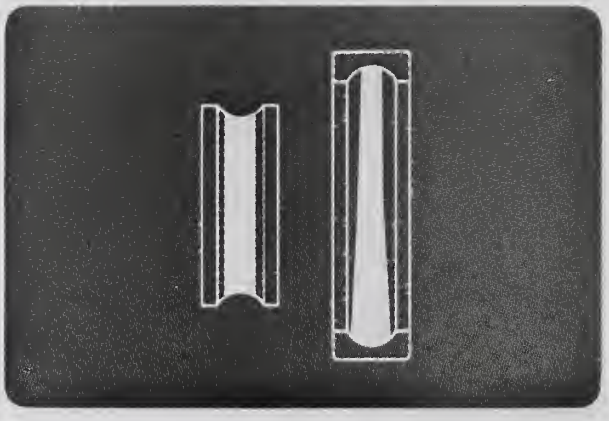
When an outer ring in a deep-groove ball bearing is misaligned relative to the shaft, you'll see non-parallel wear patterns such as this.

FIGURE 6



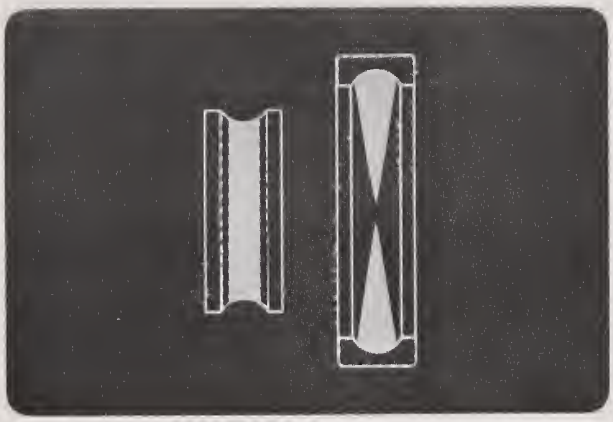
When an inner ring is misaligned relative to the housing, a pattern like this will appear.

FIGURE 7



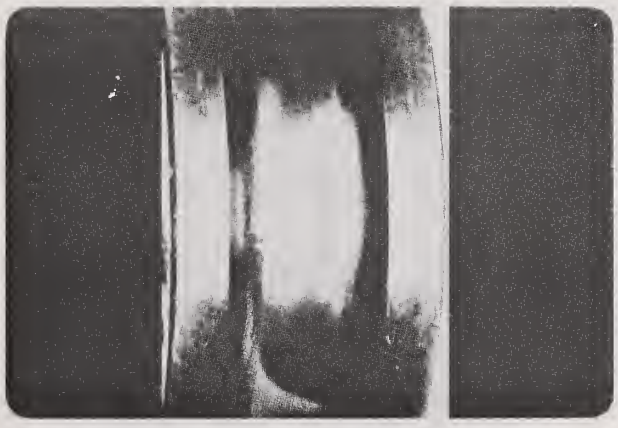
Too tight an interference fit can internally preload a bearing by squeezing the rolling elements between the rings, and that shows in a pattern like this.

FIGURE 8



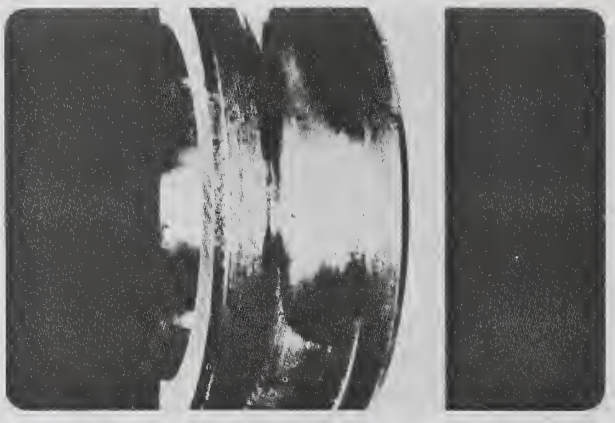
Distorted or out-of-round housing bores can radially pinch an outer ring, resulting in a wear pattern such as you see here.

FIGURE 9



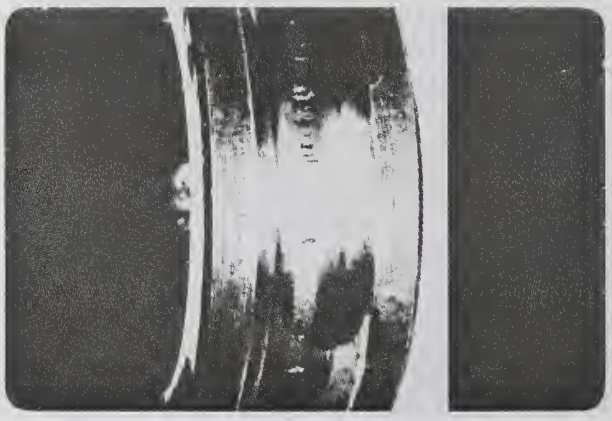
The first indication of trouble is usually a fine roughening or waviness on the surface.

FIGURE 10



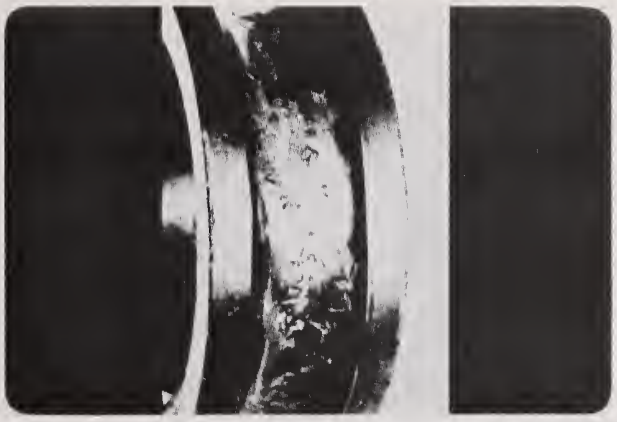
Later, fine cracks will develop.

FIGURE 11



Then spalling appears.

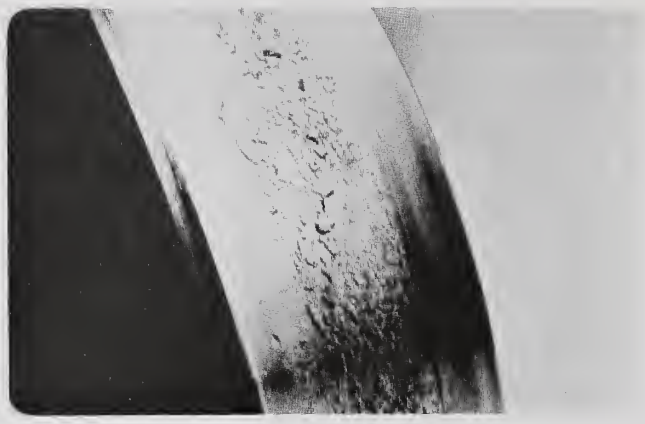
FIGURE 12



And finally, spalling occurs over the entire surface.

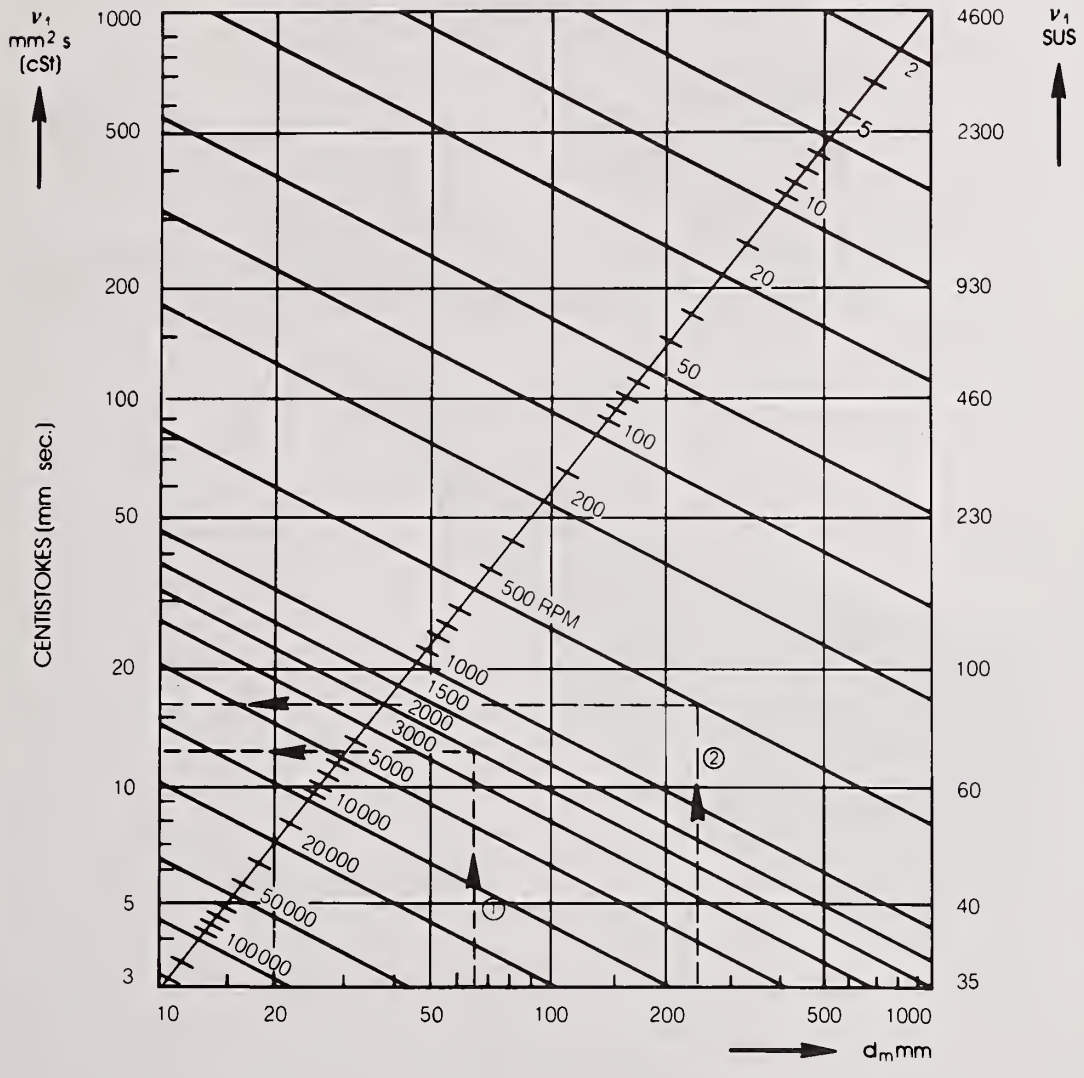
FIGURE 13

FIGURE 14



Smearing is another result of inadequate lubrication, as two surfaces adhere, and metal from one surface is actually welded to the other.

FIGURE 15

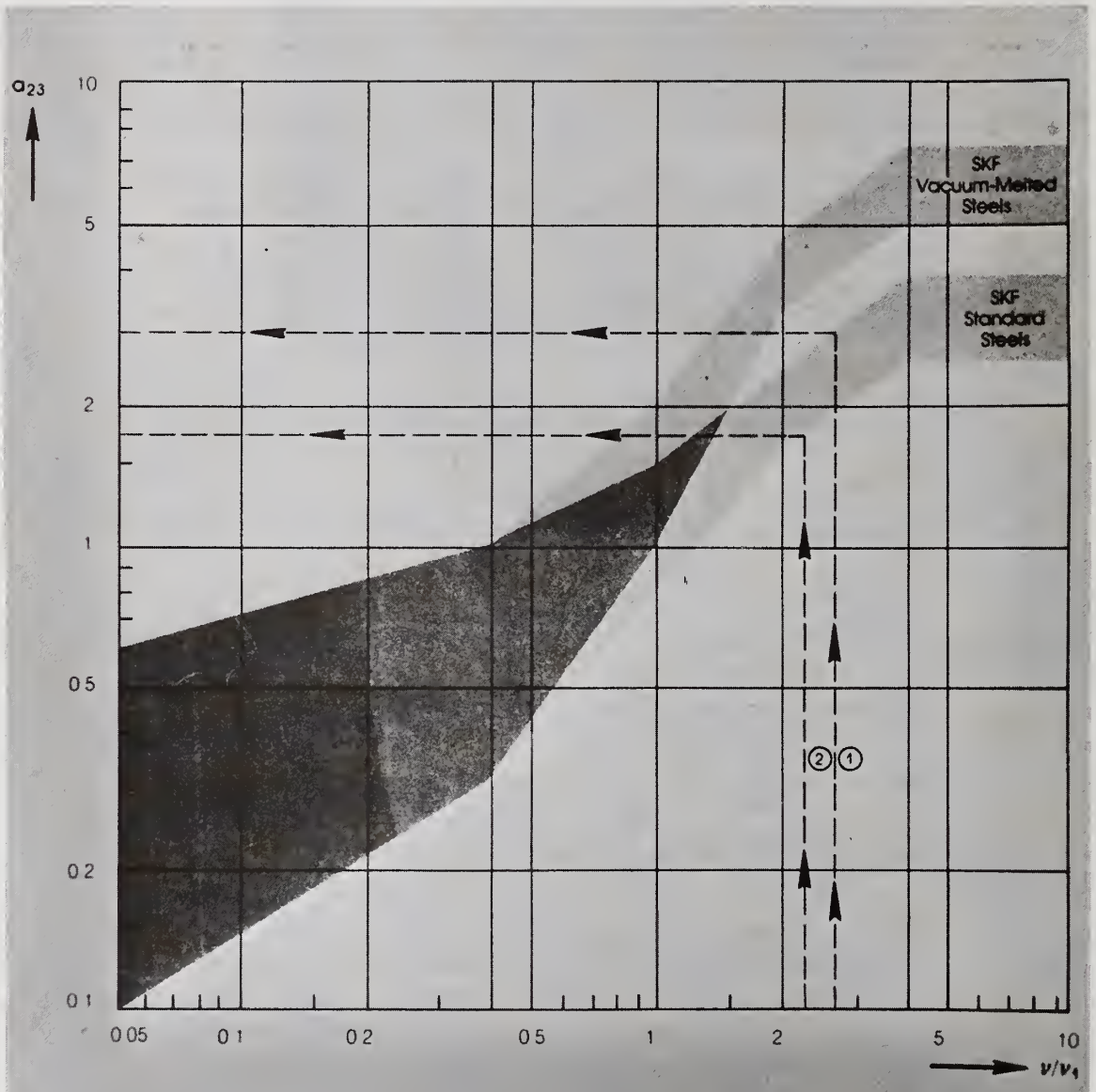


Minimum Required Lubricant Viscosity

d_m = (bearing bore + bearing O D) − 2

ν_1 = required lubricant viscosity for adequate lubrication at the operating temperature

FIGURE 16



Fatigue Life Adjustment Factor a_{23} for Bearing Materials and Lubrication

ν = lubricant viscosity in application

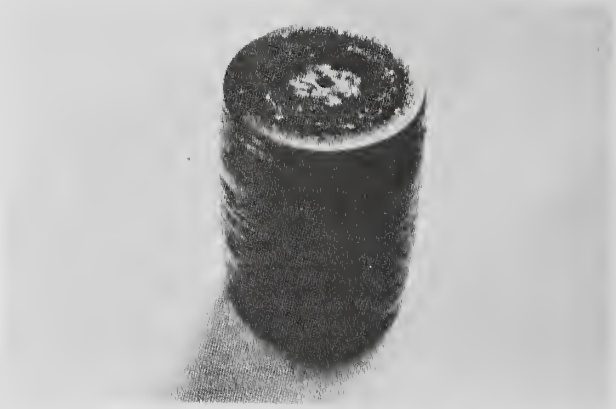
ν_1 = required lubricant viscosity from Figure 16

FIGURE 17

Abrasives can result in fast wear of both the rollers or balls and the rings, dramatically shown in this photograph.

FIGURE 18

FIGURE 19



Moisture in the lubricant can cause rusting on a roller end—or on the roller surface if it is inactive.

FIGURE 20

THE APPLICATION OF NYLON POWDER COATING TO VEHICULAR COMPONENTS

H. T. Lootens
US Army Materiel Systems Analysis Activity
Aberdeen Proving Ground, MD 21005

Abstract: Rust causes serious damage to vehicles, especially in a salt-air environment. Also, leakage or spillage of battery acid causes significant corrosion of battery-related components. Another type of corrosion occurs inside fuel filler sleeves of diesel-fueled vehicles. This corrosion deposit (lead carbonate), formed by the interaction of the fuel, moisture and the lead coating on the sleeve, can cause major problems in the vehicle fuel injection system. Approximately 1500 vehicular parts were coated with Nylon 11 to evaluate its effectiveness in the prevention of rust and corrosion. These parts included battery boxes, trays and frames, as well as fuel sleeves and frames. The characteristics and properties of Nylon 11 are summarized, the coating facilities and procedures are described and recommendations are presented.

Key words: Battery-acid corrosion; metal coating; polymer coating; rust prevention; vehicular rust.

INTRODUCTION

Rust causes widespread and serious damage to vehicles. This is particularly true when the vehicles are used around salt water because here the atmosphere is extremely corrosive. Mild rust damage to the bodies and frames of vehicles requires that the affected area be repainted. In severe cases, the vehicle may be declared not economically repairable, and the purchase of a replacement may be necessary.

In addition to environmentally-induced rust damage, vehicles suffer from corrosion caused by the leakage or spillage of battery acid. This type of damage is common on battery boxes, frames, trays, and associated hardware. As in the case of rust damage, corroded parts require either repeated painting or replacement.

Another type of corrosion, normally seen inside the fuel filler sleeves of diesel vehicles, is caused by the interaction of diesel fuel, air (moisture), and the lead coating on the filler sleeve. A white, pasty deposit (lead carbonate) forms on the inside of the sleeve and the underside of the filler cap. Unless this deposit is cleaned off, it

will get into the fuel tank and can create major problems in the fuel injection system of the vehicle.

One of the most effective methods of preventing rust and corrosion damage is to protect the metal surfaces with a coating of Nylon 11. The coating is applied in powdered form by electrostatic deposition and is fused to the metal surface with heat. Coatings of this type have been used industrially for a number of years, and have proven to be extremely resistant to rust and corrosion.

The Field Equipment & Technology Division, US Army Materiel Systems Analysis Activity (AMSAA) recently completed a project to evaluate the effectiveness of Nylon 11 on Army vehicular components. Working jointly with the US Army Ordnance & Chemical Center & School (OCCS), approximately 1500 vehicular parts were coated at the OCCS from December 1977 through February 1978. The coated parts included battery boxes, trays, frames, brackets, braces, and holddown bolts; fuel sleeves and sleeve frames; and miscellaneous OCCS training aids.

This paper presents a summary of the properties and uses of Nylon 11, describes the AMSAA-OCCS powder coating facility and procedures, identifies the parts that were coated, and recommends future action.

BACKGROUND

In early 1977, personnel from the Naval Air Development Center (NADC), Warminster, PA presented a briefing at AMSAA in which they described the Nylon 11 powder coating technique. They had been using this type of coating on a variety of naval aircraft and ship components since 1970 in order to reduce rust and corrosion and to improve wearability.

In October 1977, representatives from AMSAA visited NADC to observe their powder coating facility and learn more about the technique. NADC personnel indicated that they had assisted the US Marine Corps in setting up a small powder coating facility at Camp LeJeune, North Carolina approximately twelve months earlier. The AMSAA-OCCS coating project was discussed, and NADC personnel stated they would support such a program with their technical guidance and equipment.

In November 1977, AMSAA personnel visited Camp LeJeune (2d Marine Division, Force Troops and HQ, Camp LeJeune) to see their coating operation. The Marines were coating small numbers of battery frames, fuel sleeves, and sleeve frames. NADC had loaned them powder coating equipment and provided on-side technical instruction on the application of Nylon 11 coatings.

Following the visit to Camp LaJeune, AMSAA decided to proceed jointly with the OCCS in a powder coating project. The objective of this proj-

ect was to obtain a data base on the effectiveness of Nylon 11 when applied to components of Army vehicles.

CHARACTERISTICS AND PROPERTIES OF NYLON 11 POWDER COATINGS

Nylon 11 is a thermoplastic polymer produced from a vegetable source, rather than a petroleum source. It was introduced on the market a little more than twenty years ago, and offers the following advantages when applied to a metal surface:

(a) Excellent corrosion resistance.

(b) Improved abrasion resistance and wearability.

(c) High impact resistance.

(d) Good fungus and stain resistance.

(e) Good outdoor weathering properties.

(f) Good electrical properties.

(g) Good resistance to toxic agents and ease in decontamination, compared to alkyd paint.

The use of the powder coating technique to protect metal surfaces has several advantages over other coating methods and materials. The first and probably most significant advantage, especially from an ecological standpoint, is the elimination of the use of solvents in the coating process. The absence of solvents provides a virtually pollution-free atmosphere. Other safety standards are also improved because the fire hazard in the work area is substantially reduced. The second advantage that results from the use of powder coating technology is its ability to form a protective resin coating that cannot be applied in any other manner without difficulty, primarily because of the poor solubility of the resins in most solvents. Thus, many coating properties can be obtained that were not previously available. The third advantage of powder coating is that almost none of the powder is wasted. The oversprayed powder is easily collected and reused.

One method used for coating metals with Nylon 11 powder is the Electrostatic Process. In this process, the powder is passed through a nozzle carrying a high electrical potential (20-60 KV). The powder particles become charged and are attracted to the metal part, which is at zero potential. The thickness of the coating is a function of the static attractability of the charged particles and the mechanical packing of the dry powder. Since Nylon 11 is a thermoplastic, it is only necessary to melt the adhered powder in an oven to fuse the coating to the metal

surface. Fusion temperatures range from 400 to 450°F.

Most metal parts can be coated with Nylon 11 provided they can withstand the fusion temperature without undergoing a physical change or a dimensional distortion. All parts to be coated must be thoroughly cleaned to remove oil, grease, paint, rust, and corrosion. A primer coat is often used to improve the adherence of the Nylon 11 powder and to provide additional protection for the metal in the event the coating becomes scratched or chipped.

Table 1 is a summary of the properties of the Nylon 11 powder used for this project.

Table 1. Properties of Nylon 11 Powder for Electrostatic Deposition

Nomenclature	Fine Powder ES
Grade	Functional
Manufacturers code	RDP-15
Standard colors	Black, White, Grey, Beige, Light Green, Dark Green
Custom colors	Red, Light Blue
Particle size	0-80 microns
Fusion temperature	430-450°F
Film thickness	2 mils (minimum) 7 mils (maximum)
Melting point	360-365°F
Dielectric Strength at 68°F, 65% RH	
3 mil coating	4.62 KV
8 mil coating	9.93 KV
Spray gun voltage	20-60 KV
Spray gun distance	8-12 inches
Coverage	160 sq ft per mil per lb

ORGANIZING THE COATING FACILITY

AMSAA arranged with the Mobility Department (OCCS) to coat selected components from the vehicles used as training aids in the department. Since both AMSAA and the OCCS are located at APG, the logistical and management problems of working with their vehicles would be minimized.

The components to be coated were battery boxes and related hardware, fuel filler tubes, and fuel filler tube frames (these latter two items are referred to in this report as fuel sleeves and sleeve frames). The sandblasting and degreasing of the parts was performed by personnel of the Materiel Testing Directorate (MTD), US Army Test and Evaluation Command, Aberdeen Proving Ground, Maryland.

NADC loaned AMSAA an oven, a coating control console and a powder spray gun. Under contract, they provided a second control console and gun, Nylon 11 powder and primer and many other expendable supplies. They also presented an initial briefing on the coating process to AMSAA-OCCS personnel at Aberdeen Proving Ground, and furnished a two-man team to give on-site technical assistance for a one-week period at the beginning of the project.

In order to fuse the coating on the larger parts, AMSAA requested that the Metal Surfaces Department (OCCS) build a large oven. This oven (Figure 1) was approximately 4-feet square with an inner wall of 16-gauge steel and an outer wall of 1/8-inch steel. It is insulated between the walls with 2 inches of fiberglass, and is heated with four electric stove elements. The elements are connected in pairs and each pair is thermostatically controlled with a separate set of oven controls taken from a household stove. It achieves a temperature of 500°F within ten minutes and maintains the desired setting within $\pm$ 5°F.

A training shop area in the Mobility Department was chosen to set up the coating facility. A compressed air supply (100 psi) was available in the shop, and the Facilities Engineering Directorate at Aberdeen Proving Ground installed two 30-ampere electrical outlets to power the large oven. The NADC oven was wired directly into the circuit breaker panel.

DESCRIPTION OF THE COATING PROCEDURE

Initial Marking of Parts

The parts to be coated were removed from the vehicles and marked so they could be returned to the vehicle from which they were taken. This is particularly important when parts are being collected concurrently from a number of vehicles belonging to different local units. It avoids confusion (and arguments) later if all parts are marked at the time of

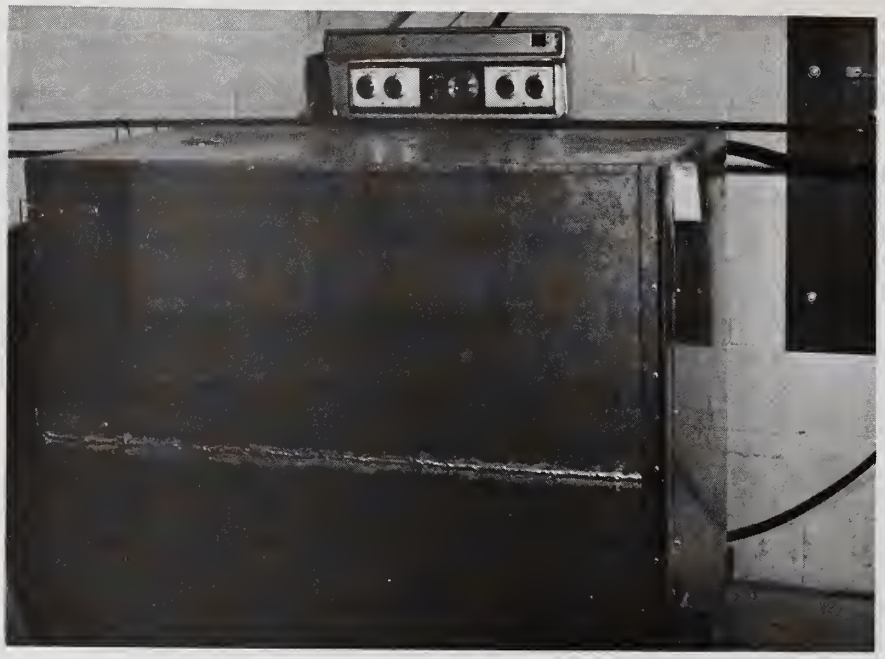


Figure 1. Large oven built at Aberdeen Proving Ground.

pickup. Metal dog tags are ideal for this purpose. They can be stamped with the vehicle number and then wired to the part. At the conclusion of the coating process, the tag will still be legible and can be used to assure that each part gets reinstalled on the proper vehicle.

Sandblasting

The parts were sandblasted to remove all paint, grease, dirt, etc. To sandblast a large number of parts in a relatively short time (particularly large parts such as battery boxes and frames), required the use of machine shop, heavy-duty sandblasting facilities.

Various types of sandblasting machines were used, including Hydro-Finish (Vapor Hone), tumble blasters, rotary blasters and hand-held hose type blasters.

Degreasing

After sandblasting, the parts were degreased to remove the blasting residue and any dirt that accumulated because of handling. Small parts, such as fuel sleeves, sleeve frames, and battery holddown rods, were

degreased in an approved, portable solvent tank, using xylene (or equivalent) as the solvent, with a final wash in a tank of denatured alcohol. Adequate ventilation must be provided when using these solvents.

To degrease large parts such as battery boxes or frames in a portable tank is not practical. To do this job efficiently requires a vapor degreaser. The solvent used in this type of degreaser is trichloroethylene heated to 250°F. The parts are put into a metal basket and lowered into the solvent fumes for a few minutes. When removed from the basket, the parts dry almost instantly and are completely free of grease and dirt.

After degreasing, parts should be handled with cotton work gloves throughout the rest of the coating process to avoid contamination of the metal surface.

Priming

Before coating, the parts were primed with a zinc phosphate primer. As mentioned earlier, the primer improves the adherence of the coating and provides additional protection for the metal in case the coating is broken. The primer was applied with a special apparatus consisting of a small CO_2 gas can, a primer bottle, and a trigger-type spray head. When the gas can was exhausted, it was easily replaced with a new can. Figure 2 shows the primer being applied to a fuel sleeve. Care must be exercised to avoid putting on too much primer. The optimum is a 0.3 mil thick coat, with no runs or sags. It is also important to allow primed parts to dry completely (5-10 minutes at 72°F) before applying polymer powder.

Coating (Electrostatic Method)

For coating, the parts must be electrically grounded. This was accomplished by suspending them with wire from a metal rod in the powder booth. The rod was grounded to the coating control console, and the entire inside of the booth was metal-lined and grounded to an earth ground. The nylon powder is positively charged as it leaves the spray gun, and is attracted to the grounded part. The thickness of the powder coating can be varied from 2-7 mils, and is a function of the potential difference between the part and the powder particles. Generally, best results are obtained with a 4-5 mil thick coating. This can be achieved consistently with proper adjustment of the control console and an experienced operator.

The booth has a 12-inch circular fan in the lower part of the rear wall that draws air through the front of the booth. This air flow pulls the powder into the booth and keeps it from collecting on the operator's hands and arms. The fan also pulls the oversprayed powder down through

Figure 2. Priming a fuel sleeve.

a funnel-shaped opening in the bottom of the booth, where it is collected and reused. A filter inside the booth prevents powder from being exhausted into the work area. This arrangement insures almost no loss of powder, which is one of the advantages of the powder coating technique. Figure 3 shows the nylon powder being sprayed on a 5-ton truck battery box.

The flow of powder and the charge on the particles is controlled by the control console. The unit used was the INTERRAD/GEMA Model 710 and consists of a powder hopper, a control module, a lightweight manual spray gun, and the necessary hoses and cables. The control module output is 12 volts AC or less, since the high-voltage power supply is built-in to the spray gun; therefore, there is no high voltage cable from the module to the gun. Four electrodes charge the powder particles inside the gun barrel from 0-70 KV (variable). The control module has controls for high voltage, compressed air, and powder flow rate. The spray gun operates at 80-100 psi (3-5 cfm), and is equipped with an adjustable automatic safety shutoff to limit output current. The powder spray pattern can be easily adjusted, while spraying, by changing the position of the deflector extending from the gun nozzle.

Figure 3. Applying nylon powder to a truck battery box.

The parts being powdered must be solidly grounded so that the powder will adhere properly. To accomplish this, the metal rod in the booth and all connections between it and the parts are blown clean with a low pressure air hose before beginning to spray the powder. Once the parts have been coated, they must not be touched or the powder will come off. If this does occur accidentally, the part should be returned to the booth and the marred area repowdered.

Fusion of the Coating

After coating, the parts were suspended in an oven at a temperature of 425°F for approximately fifteen minutes. This fusion time will vary depending on the thickness (mass) of the part (thicker parts require a longer time to achieve fusion temperature). When the powdered surface of the part appears shiny and wet, it is ready to be removed from the oven and allowed to cool. It is important not to leave parts in the oven too long or cure them at too high a temperature, because excessive heat will cause the coating to begin to run off. Also, care must be exercised when heating fuel sleeves, since excessive heat will cause the solder around the filter screen to melt and drip out.

Care must be exercised when removing heated parts from the oven. Small parts can easily be handled with pliers. The 5-ton truck battery boxes, however, weigh 28 pounds, and are much too heavy and unwieldy to handle with pliers. For this reason, two special tools were fabricated to move the boxes from the powder booth to the oven and to remove them from the oven. The battery box is suspended by its handles from a T-hook, and a forked rod engages the vertical section of the hook to lift the box.

IDENTIFICATION OF THE COATED PARTS

Table 2 shows the types of parts coated and the number of each. In general, the battery boxes, battery box frames, battery holddown frames, battery trays, battery brackets, and transmission stands were heat-cured in the large oven because of their size. The fuel sleeves and sleeve frames, chains and slides, and the smaller battery frames and holddowns were processed in the NADC oven.

Table 2. Summary of Parts Coated

Item	Quantity
Battery Box	133
Battery Box Frame	16
Battery Hold-Down Bolt	736
Battery Hold-Down Frame	280
Battery Tray	55
Battery Bracket	11
Battery Brace	11
Fuel Sleeve	179
Fuel Sleeve Frame	48
Chain and Slide	32
Transmission Stand	6
TOTAL	1507

Table 3 indicates the number of coated parts from each vehicle. The ratio between battery bolts and frames is not consistent because some of the frames had missing bolts. This created some confusion when the finished parts were being returned to the local units, and serves to emphasize the fact that all parts must be positively marked when removed from the vehicles.

Figure 4 shows a variety of finished parts. Figure 5 is a severly corroded battery tray and a new tray from an M151A2 vehicle. Figure 6 shows a coated and uncoated 5-ton truck battery box. The damaged parts in these two photographs dramatically illustrate the effects of battery acid corrosion. Many deteriorated parts similar to these were coated during this project, to minimize further corrosion damage.

To powder coat the parts described in this paper the materials shown in Table 4 were required.

Table 4. Bulk Supplies Used

Item	Quantity
Nylon 11 Powder, Dark Green 5151 Functional Grade, Type RDP-15 Rilsan Corporation Glen Rock, New Jersey	100 lbs
RILPRIM Primer, Type 104A & 104B Rilsan Corporation Glen Rock, New Jersey	5 gals (each type)
Methyl Ethyl Ketone (MEK)	2 gals
Xylene	55 gals
Alcohol, Denatured	20 gals

REQUIREMENTS FOR A LARGE-SCALE COATING FACILITY

A large-scale powder coating operation can be conducted in any suitable, indoor area where sufficient electrical capacity, a compressed air supply and adequate ventilation are available.

The sandblasting and vapor degreasing facilities are absolutely essential in order to coat many, large parts in a relatively short time. These parts, particularly 5-ton battery boxes and battery box frames require the use of heavy-duty sandblasting equipment, and they cannot be degreased conveniently without a vapor degreaser. This type of

Table 3. Coated Parts Listed by Vehicle Type

Item*	M151A2	M880	M561	M35A2	M813 M816	M123A1C	M559	Fork Lift	M113	Lube Unit	300 amp Test Std.
1	-	-	-	19	80	12	-	-	-	6	16
2	-	-	-	-	-	-	4	-	12	-	-
3	88	20	30	90	320	90	20	30	48	-	-
4	74	11	18	19	80	12	8	18	-	26	14
5	44	-	-	-	-	6	-	-	-	5	-
6	-	11	-	-	-	-	-	-	-	-	-
7	-	11	-	-	-	-	-	-	-	-	-
8	-	-	18	19	79	24	30	9	-	-	-
9	-	-	18	-	-	-	30	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	32
11	-	6	-	-	-	-	-	-	-	-	-

*1. Battery Box
2. Battery Box Frame
3. Battery Hold-Down Bolt
4. Battery Hold-Down Frame
5. Battery Tray
6. Battery Bracket
7. Battery Brace
8. Fuel Sleeve
9. Fuel Sleeve Frame
10. Chain and Slide
11. Transmission Stand (training aid)

Figure 4. Typical coated parts.

Figure 5. A corroded and a new battery tray.

Figure 6. A coated and an uncoated truck battery box.

equipment is normally found in large machine shops or foundries. Any local military unit desiring to use the powder coating technique should make sure that such facilities are available very early in the project. The other critical item is an oven large enough to accommodate whatever parts are being coated, and capable of achieving a temperature of 450°F. There are, however, numerous ovens commercially available for rent, so the problem of oven availability is probably easier to solve than the problem of locating sandblasting and degreasing facilities.

ADDITIONAL COATING EFFORTS

In order to obtain additional field data on the rust and corrosion resistance of Nylon 11 coating in a salt water atmosphere, AMSAA assisted the 2d Marine Division/Force Troops/Marine Corps Base, Camp LeJeune, North Carolina in setting up a large-scale facility for coating vehicle components, similar to the program described in this paper. The AMSAA-OCCS coating team provided technical advice, equipment, and supplies to help them convert their current coating facility to a large-scale operation. This project was completed in June 1978.

SUMMARY

The feasibility of the use of Nylon 11 powder coating as a rust and corrosion preventative has been demonstrated in the laboratory and in numerous industrial applications. The AMSAA-OCCS powder coating project will provide the Army with field data on the value of this coating for tactical vehicle components under a variety of environmental and use conditions.

A test performed by the Army Chemical Systems Laboratory in 1978 showed that Nylon 11 coating resists toxic agent sorption far better than the alkyd enamel currently used on Army vehicles. The nylon coating does not resist toxic agents as well as polyurethane paint, however. Of course, the spray application of any urethane coating requires that strict safety procedures be observed. For this reason, polyurethane paint has not been approved for use by tactical field units as yet.

If the long-term wear characteristics of this coating prove acceptable, we would recommend the Army-wide use of such a coating for selected vehicle parts. The most cost effective and practical way to implement an Army-wide program would be to coat the parts at the time of manufacture, rather than later. If parts were coated when new, it would avoid the expense of sandblasting and degreasing. This, coupled with the savings realized by eliminating the final finishing process, would make Nylon II powder coating competitive with current methods of protecting metal surfaces.

ALTERNATIVE ANTISTATIC PACKAGING MATERIALS FOR PRECISION BEARINGS

Marianne K. Bernett and Harold Ravner
Naval Research Laboratory
Washington, DC 20375

Abstract: Precision instrument bearings currently are packaged in polyetheylene or nylon films containing minor amounts of antistatic agents. A previous NRL study showed that the presently used surface-seeking antistatic agents adversely affect the contacting bearing metal surface and/or bearing lubricant. To ameliorate these problems, the following alternatives were investigated: 1) chemically characterized antistatic agents either incorporated into or topically applied to the polymer films; 2) alternate packaging materials. Effects of exposure of these alternatives to pure lubricants, lubricated steel surfaces, and clean steel surfaces were examined. The results provided information on possibly deleterious transfer of the antistatic agent to any contacting surface affecting lubricant properties and surface wettability.

Key words: Antistatic agents; precision instrument bearings; bearing packaging materials; antistat-lubricant interaction; antistat-bearing steel interaction; lubricant displacement; bearing steel wettability.

To minimize exposure to atmosphere-borne particulate contamination during transport or storage, precision instrument bearings are often packaged in ultraclean polymer (nylon or polyethylene) containers. Since electrostatic charges tend to accumulate during normal handling, polymeric films are now commercially available with incorporated antistatic agents (antistats). However, these currently used long chain, surface-seeking surfactants (1) in contact with lubricated miniature bearings can migrate from the polymer surface to the lubricant and ultimately to the bearing surface (2), adversely affecting the operational characteristics of the bearings, particularly with regard to torque changes and wear due to lack of lubricant.

The present investigation examines the interactions of several alternate chemically characterized species of antistats as well as a multi-laminate antistat-containing polymer film with instrument lubricants and bearing metal surfaces. All materials used, their chemical identities, and convenient abbreviated codes are listed in Table I.

Table 1

Antistatic System Components

Component	Identification	Code
Lubricant	Synthetic Hydrocarbon, base stock	SHC-B
Lubricant	Synthetic Hydrocarbon, formulated	SHC-F
Lubricant	Polyolester-Diester, formulated	MB-20
Antistatic Agent (Internal)	Polyethylene glycol mono-laurate	PEG
Antistatic Agent (Internal)	Lauric diethanol amide	LDA
Antistatic Agent (Internal)	N-N-bis(2-hydroxyethyl) alkyl amine	BHA
Antistatic Agent (Topical)	Alkyl 4^{e} ammonium chloride	AAC
Polymer	Polyethylene	PE
Polymer	Nylon	NY
Polymer	Multilaminate	ML

Depending on their molecular function, antistatic agents may be either incorporated into polymer packaging as internal additives, or applied topically. In this study PEG, LDA and BHA were investigated as incorporated polymer components (5% by weight) and AAC (0.26% by weight) as a topical coating (3), which was painted onto the surfaces of either PE or NY films and air-dried. We also examined a commercial static-shielding bag (4), fashioned from a multilaminate sheet consisting of three electrically distinct layers: a conductive nickel outer layer (40% light transmission), a polyester central layer, and an inner layer of PE containing the antistat (5) identified as PEG (6).

The specific interactions studied included: 1) migration of the agent into the lubricant and its subsequent solution; 2) chemical or physical change of the lubricant; 3) displacement of the lubricant from the bearing surface by the agent; and 4) adsorption of the agent on the bearing surface preventing respreading or rewetting by the lubricant.

All pure antistatic agents deposited as drops on the surface of thin films of the lubricants surface-chemically displaced (7) the latter from steel substrates. Regardless of the specific interactions involved,

a universal effect on the substrate was the appearance of a "dry" area adjacent to or surrounded by retracted liquid. The failure of the displaced liquid to respread over it, as well as the nonspreading of a freshly placed drop of the pure lubricant, attested to the intractable nonwettability of the "dry" surface. Effects of the antistats on the lubricants ranged from solubility of the antistat in the lubricant with concomitant change in the properties of the latter, to complete immiscibility.

Minor amounts of the antistats incorporated into, or topically applied to the polymer material had various effects on lubricant and substrate during extended contact with the lubricated steel surface. After removal of the antistat-containing polymer, composition of the lubricants remaining on the steel substrates were determined by FTIR. Each FTIR spectrum was compared with those of the respective pure lubricant and pure antistat: as an example, subtraction of the spectrum of pure SHC-B (Figure 1b) from that of the liquid remaining on the surface after SHC-B had been in contact with PE + PEG (Figure 1a) resulted in the spectrum in Figure 1c, whose prominent features corresponded to those of PEG (Figure 1d). This established transfer of the additive into the lubricant. However, under adsorption/ desorption equilibrium conditions, the low concentration of PEG in the lubricants was insufficient to displace the lubricants from the steel surface. Other antistats, such as BHA, not only thickened the lubricant, but were sufficiently surface-active to migrate through it, strongly adsorb onto the substrate, and displace the liquid.

Extended contact of antistat-containing polymer with the unlubricated steel surface resulted in antistat transfer to the surface, as observed visually after separation of surface and polymer film. To ascertain whether the affected steel surfaces were wettable by either lubricant or antistat, contact angles (θ) of each liquid were measured on the "dry" portion of the surfaces. The most wettable surface was from contact with ML, the low θ being evidence that the surface was virtually free of organic adsorbants.

The various displacement mechanisms showed that lubricant-insoluble antistats are not suitable if they either strongly adsorb on the solid substrate to form an oleophobic film or chemically interact with the lubricant. Topically applied agents, especially those whose chemical structure contain corrosive or hydrolysis-promoting ions, appear to be unsuitable for long-term protection of delicate instrument bearings.

Of the antistat polymer combinations studied, ML had the least deleterious effects on steel substrates and/or lubricants. Although, after prolonged contact, traces of the agent were detected in the lubricant by FTIR analysis, no adverse reactions, i.e., nonwettability of substrate or physical changes of lubricant, was observed. The problems of static build-up, its dissipation, and the precautions necessary with antistatic plastic use have been widely discussed (8,9). Multilayer

laminated containers, as exemplified by ML, may overcome many of these problems (5). However, two general problems remain which this study has not addressed: 1) the tendency of packaging material (with or without antistatic additives) to slough off in contact with solid surfaces (9) causing major problems in critical applications, e.g., instrument bearings, etc. and 2) the long-term effects of the antistats on such important lubricant properties as stability, deposit formation, and antiwear activity.

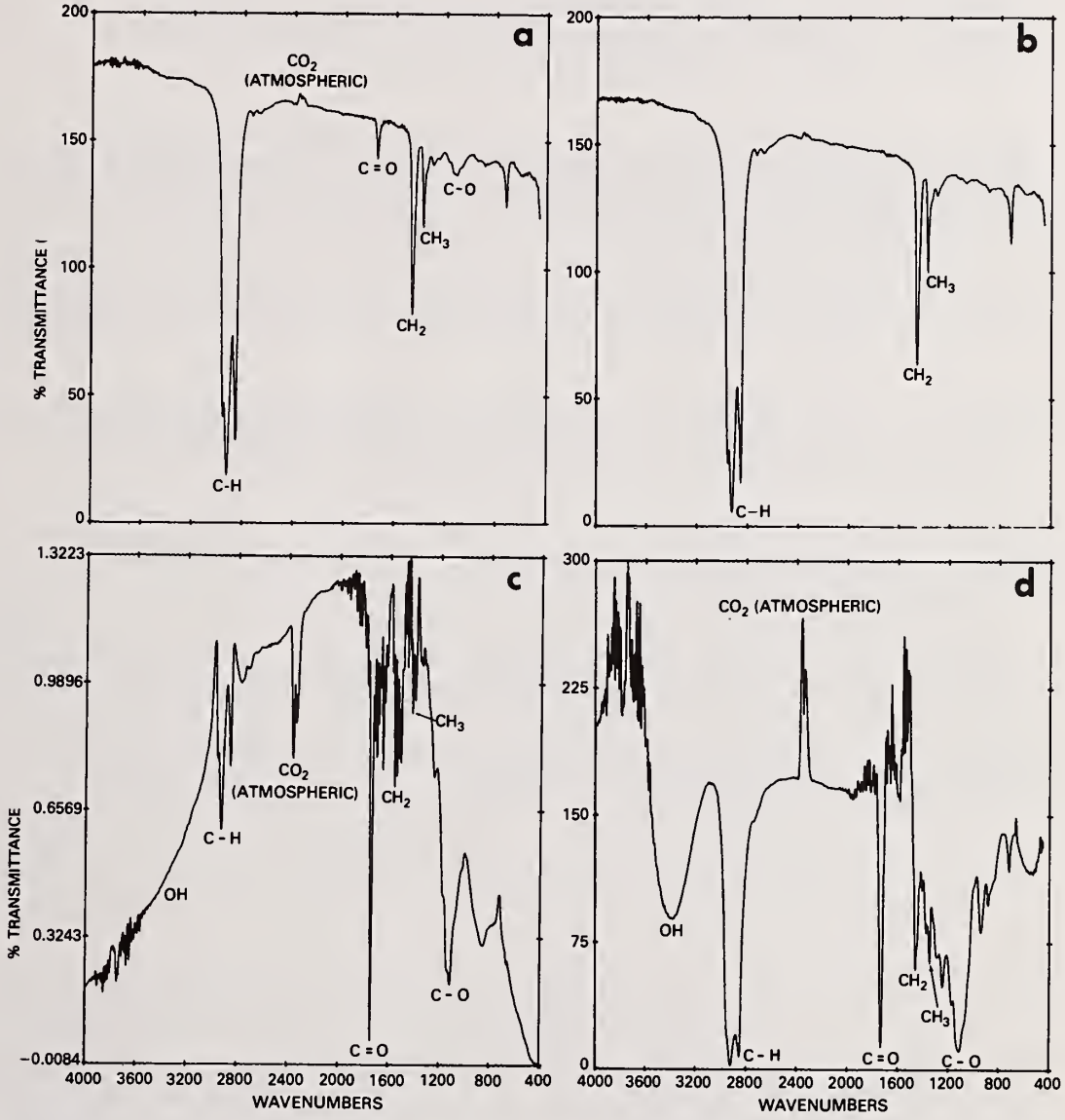


Figure 1: Antistatic Agent Transfer from Antistat-Containing Polymer Film to Lubricant After 5 Months Contact as Monitored by FTIR Spectra. a) Liquid Remaining on Substrate After Contact of SHC-B with PE + PEG; b) Pure SHC-B; c) Component Remaining After Subtraction of Fig.1b from Fig.1a; d) Pure PEG

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A THERMAL PREDICTION TECHNIQUE FOR EXTENDING IN-SERVICE LIFE OF ROLLER BEARING ASSEMBLIES

B. R. Reason
Cranfield Institute of Technology
Cranfield, Bedford MK43 OAL, England

V. A. Schwarz
Escola Federal de Engenharia de Itajuba
Itajuba, M.G., Brazil

Abstract: A programme is described involving the measurement of spacial temperatures in a rolling contact bearing assembly. A technique of thermal analysis, amenable to computer programming, is presented and the results from this compared with the experimental findings. The paper concludes with a discussion on the temperature correlation obtained and the thermal factors influencing premature bearing failure.

Key words: Bearing failure; bearing reliability; condition monitoring; roller bearings; thermal analysis.

I. INTRODUCTION

Premature failure of rolling contact bearings arising from temperature effects is a common phenomenon. In a given design situation when parameters such as applied load, operating speed, lubricant characteristics and bearing and housing geometries are specified it is obviously of great importance if the designer is in a position to predict the spacial temperature distribution at specific points within the unit. Furthermore, for units which are already in service the ability to predict local operating temperatures gives the bearing user an assessment both of the likelihood of thermal failure hazard and the capability, from the thermal standpoint, of anticipating the ramifications arising from any planned increase of duty specification.

Previous attempts at a tractable solution of the theoretical problem had been gravely hampered by an inadequate knowledge of the spacial division of the generated heat between the component parts of the bearing assembly, together with the heat 'take-up' of the lubricant itself. Additionally, though to a lesser degree of importance, a paucity of information on the choice of suitable heat-transfer coefficients existed.

To circumvent these problems and to provide a firm foundation for an analytical approach it was decided to build a fully instrumented test rig to provide an experimental yardstick against which the veracity of any theoretical approach might to tested and a viable programme ultimately produced.

In the field of condition monitoring, should a programme exist from which temperatures can be predicted at specific points from one single temperature measurement (such as oil bath temperature) then the question of premature thermal failure could clearly, be greatly mitigated. In short, the direct result of employing such a system would be better overall bearing reliability and an extended service life.

It is the aim of the present paper to present such a system from both the practical and theoretical standpoints and to invoke the user/designer's confidence by demonstrating the degree of correlation which has been obtained between the two.

2. EXPERIMENTAL STUDY

2.1 Object

The experimental work herein described was carried out on a specially instrumented rolling contact bearing test rig which gave the following measurement capabilities.

(a) Bearing load (radial and axial).
(b) Test shaft rotational speed.
(c) Bearing friction power losses.
(d) Spacial temperature distributions within bearing components, shaft, housings and at specific points in the bedplate/foundations.

2.2 Rolling Contact Bearing Test Rig

The test rig configuation consists essentially of a drive test shaft which may, optionally, carry three or four rolling contact roller bearings of various types, mounted in selected housing configurations. Fig. 1 shows the general arrangement and indicates two typical bearing options on the central section.

Power is supplied to the rig from a 3H.P., 50 cycle three-phase electric motor via a hydraulic variator unit. This allowed stepless speed variation from 0 to 1400 r.p.m. at the variator output shaft. Intermediate between the test module and variator, a slave pillow block unit carries a flexible coupling at its input drive to the test shaft and a pulley and flat belt drive at its other end to a second pulley at the variator output. This system allows a speed step-up to a

maximum of 5600 r.p.m. at the test shaft and circumvents the problem of belt drive forces acting on the test bearings.

To eliminate transmitted bedplate vibrations the test module and drive system are separately mounted on mild steel, surface-ground gauge plates of 40mm thickness, these being grouted and bolted to a large concrete foundation block. The system has been found in other test rig designs to provide maximum drive energy dissipation, thus minimising extraneous vibration effects on the test module proper. The foundation block itself is mounted on rubber pressure mats to dampen ground vibration from outside sources.

2.3 Test Rig Evolution

The test module evolved in three distinct stages concomitant with testing requirements.

Stage 1 is delineated in fig. 1 as the area above the shaft centre line. Two identical taper-roller bearings, mounted back-to-back on the test shaft, are contained within a cylindrical sleeve. The latter rests on a hydrostatic bearing (9)*, which applies radial load to the system. Reaction to the applied load is provided by two identical plain roller bearings, the forward one being mounted in a conventional mount (3) whilst the rear bearing is carried in an inverted hydrostatic system (5). The loading block of this (4) carries a circumferential pool, a constant film thickness being maintained between it and the bearing mounting ring by the external oil pressure to the system. The test module is symmetrical about the centre-line of the hydrostatic system (9).

Stage 2 (the area below the shaft centre-line in Fig 1) shows the taper-roller bearing arrangement replaced by a single double-row spherical roller bearing. Aluminum cooling fins (8) were also shrink-fitted to the test shaft at this stage to investigate free and forced-convection cooling modes.

Stage 3 saw the original plain roller bearings (2) of stage 1 replaced by two identical spherical roller bearings, mounted in the original housings and fitted to the shaft by special adaptor sleeves.

3. TEST RIG INSTRUMENTATION

The primary objective of the experimental testing was to monitor parameters of bearing friction torque and spacial temperature distribution throughout the bearing test module for a wide spectrum of

*Numbers in this Section refer to Fig. 1.

speed, load and lubricant viscosity combinations. This was achieved via the following systems:

3.1 Speed System

Input speed to the test shaft is monitored by an inductive proximity transducer triggered by a sixty-tooth wheel integral with the test shaft. The transducer output signal is initially amplified and then fed to a calibrated meter giving an analogue display reading directly in r.p.m. The meter can be switched to a spectrum of speed ranges in additon to 'monitor mode' function, indicating the percentage error drift with time from any initially selected speed. Warning-light indicators are activated if a required speed tolerance is exceeded.

3.2 Bearing Torque System

As already described, hydrostatic lifts operate at (5) and (9) metal-to metal contact being therefore avoided. Thus operating torques within the bearing systems mounted at these points would be transmitted to the outer mounting ring at (5) and the bearing sleeve at (9). These torques may be monitored at both points by employing twin radial tubes extending from the ring/sleeve to load-cells (7), thereby producing a push-pull reactive system to the applied torques.

The load-cells are high-sensitivity units designed, developed and constructed within the laboratory. They consist, in essence of a cruciform member of Beryllium Copper carrying a "Wheatstone" strain-gauge bridge, the assembly being mounted in a brass housing, threaded to allow vertical adjustment.

Output from the cells is amplified by high-stability D.C. differential amplifiers before being tansmitted to the recording system. The cells were specifically calibrated for both torque measuring systems. Temperature variations were accounted for during calibration.

3.3 Bearing Loads

(a) Radial Loading

Infintely variable radial loading is applied to the bearing system by means of the hydrostatic oil lift located at (9). The lift is a four-pocket system applying its load directly to the bearings mounted in the central cylindrical sleeve.

The applied load is reacted by the fixed front bearing-housing (3) bolted to the bedplate and, after being transmitted through the inverted hydrostatic system (5), is again reacted out via the twin loading pillars (6). A D.C. activated "Wheatstone" bridge of strain

gauges mounted on each pillar measures the radial load on the rear bearing. The pillars were separately calibrated in a "Denison" tensile-test machine before final assembly in the test rig. Thus radial loads can be continuously monitored throughout the test.

(b) Axial Loading

Axial preload is applied to the twin taper roller bearing system via a finely threaded nut on the test shaft, the load being measured by a proving ring mounted in-situ with the assembly. The ring carries a "Wheatstone" bridge of strain gauges and was separately calibrated before final mounting. Since the inner ring of the outmost bearing is an interference fit with the test shaft, pressurised oil injection is employed to eliminate friction between these componenets when applying axial loading.

3.4 Temperature Measurement

For purposes of assessing the spacial temperature distribution throughout the bearing unit and its housing an array of Chromel/Constantan thermocouples is used each couple being located at a specific modal point (see Fig. 2).

High hardness bearing surfaces were drilled by spark-machining for thermocouple placement.

Thermocouple and transducer output signals are transmitted to a 'Fluke' 2200B' sixty-channel data-logger for capture and signal conditioning. The makers specified an accuracy of ± 0.1°C between 0-100°C. This was confirmed on laboratory calibration.

In programming the instrument a total of fifty channels was assigned for temperature recording, the remaining ten receiving pre-amplified signals from the load and torque transducers; solid state D.C. differential amplifier being utilised for this purpose. Thermal drift on these units is< ±2μv/°C.

Thermocouples for non-rotating nodal points are connected directly to the data logger. Rotating component signals are passed through high-quality silver/silver-graphite slip rings, the rings being air-cooled to negate thermal drift. Maximum peak-to-peak noise on these units is < 20μA/mA at 10,000 r.p.m. Since output signals are in the micro-amp range, slip ring noise was not a problem.

To circumvent resistivity errors at junctions, gold-plated contacts were employed throughout the system. 'Seebeck' effects were alleviated by mounting rotating junctions on a junction disc integral with the shaft and rotating in ambient air. Temperature calibrations were made

to negate spurious temperature effects at metal connection points.

In studying the thermal equilibrium situation within the test module particular attention was directed to interfacial heat transfer, thermocouples being concentrated at specific points at either side of the interfaces (See Fig 2).

Cage temperature capture is effected by the use of trailing thermocouples on the rotating cage. All thermocouples were manufactured in the laboratory from 0.005 ins wire, junctions being formed by electrical arc welding.

Chromel/Constantan was used in preference to Copper/Constantan since certain additives in mineral oil had been found to react with copper over extended periods of time. Since it was envisaged that long term testing would be carried out on the rig the precaution was considered necessary to avoid long-term drift effects.

The data logger was programmable for various thermocouple combinations and included an electric cold junction. Cyclic nodal scanning was a further feature of the unit.

4. TEST LUBRICANTS, ROLLER BEARINGS AND COOLING FINS.

4.1 Lubricants

Mineral oil is used as the lubricant in the vast majority of bath lubricated rolling-contact bearing situations. SAE 20W, 30 and 50 oils, were selected to produce a reasonably wide range of viscosities during the tests.

Viscosity-temperature measurements were carried out on the lubricants to establish data for the theoretical part of the programme. A high accuracy "Tamson" viscometer bath carrying certified reference tubes was employed.

4.2 Bearings

The basic bearing used in the test reported herein is a plain Cylindrical Roller bearing, type MRJ. 1-3/4.

Bearing dimensions are as follows:

Bore 44.45 mm (1.750 ins), Outer Diameter 107.95 mm (4.250 ins), Radial Clearance 0.0127 mm (0.0005 ins), Width 26.9875 mm (1.0625 ins). The flange configuration is as shown in Fig 2, the cage, of machined brass, riding on the inner ring.

4.3 Cooling Fins

To study free and forced convection modes aluminum fins were employed during later testing. These were shrink-fitted to the shaft to encourage effective heat transfer at the joint interface.

5. TESTING PROCEDURE.

5.1 General Testing

Progressive "running-in" of the bearing was achieved through a gradually increasing duty cycle of speed and load. Thermal equilibrium generally manifested itself after some five hours of running.

Loads were initially fixed, the speed being varied in steps of 500 r.p.m. from 500 to 5000 r.p.m. Speed increments generally took approximately one hour to stabilise after initial "warm-up" running of the rig.

5.2 Specific Testing (with Convective Shaft Cooling)

To study in some detail the influence of heat transfer directly from the surface of the test shaft, cooling fins as outlined under 4.3 were employed:

(a) Fins With Air Jet: Compressed air was blown tangentially onto the rotating fins in the direction of the rotation, readings of temperature and torque being taken on attaining thermal stability. Bearing duty was the same as in the initial part of the programme.

(b) Fins Without Air Jet: As (a) but without employing compressed air impingement.

6. RESULTS

6.1 Experimental and Theoretical Correlation

Fig. 2 shows typically measured temperatures for the front bearing unit. Predicted theoretical values given by the computer programme at relevant nodal points are included to indicate the correlation with the experimental results. The degree of agreement is noteworthy.

6.2 Effect of speed on Torque and Nodal Temperatures

Fig. 3 indicates, as a typical case, the general trend of torque and nodal temperatures with varying speed. The particular example is taken at a constant radial load of 2000 N using an SAE 30 oil.

6.3 Effect of Forced Air Convection

Fig. 4 illustrates directly results obtained with and without air jet cooling. Both temperature and flow rate of the jet air stream could be measured. The particular example is for an ambient air stream of 586 l/min continuously applied. The radial load was 8 KN the lubricant being an SAE 30 oil.

A general discussion of all the results obtained appears in the Section (9) "Discussion of Results".

6.4 'Heat Generation' and 'Heat Dissipation'

Fig. 5 shows both 'Heat Generation' and 'Heat Dissipation' curves plotted against temperature for two mineral oils, an SAE 50 and an SAE 30. Torque is also plotted on the ordinate.

The 'Heat Generation' curves might, on initial inspection, appear contradictory in that as the heat generation falls, the temperature increases. In the context of their interpretation a temporal element should be envisaged. At the initial stage of a test the temperature is low and the corresponding oil viscosity therefore high. As testing proceeds the temperature increases, decreasing the oil viscosity and consequently the heat generated.

7. THEORETICAL PREDICTION OF SPACIAL TEMPERATURES AND HEAT GENERATION

7.1 Modes of Heat Transfer Employed

In studying the thermal equilibrium of the bearing assembly and its surroundings the three basic modes of heat-transfer were employed, namely conduction, convection and radiation. These may be separately considered as follows:

(I) Conduction

(a) Solid

For radial conduction within the bearing rings and shaft the modified standard Fourier expression was employed viz:

$$Q_{i-o} = \frac{2\pi k\, W(t_i - t_o)}{\mathrm{Log}\left(\frac{R_o}{R_1}\right)} \qquad (1)$$

This expression was modified by Wong (1)* as follows for conduction from the inner circular surface of the bearing housing to its horizontal and vertical planar surfaces viz:

$$Q_{i-o} = \frac{2\pi k\, W(t_i - t_o)}{\text{Log}\left(f \cdot \frac{a}{R}\right)} \qquad (2)$$

The thermal conductivity 'k' used in the above expression is a function both of the material and its temperature level. The latter variation is of second-order importance and was therefore neglected.

(b) Interfacial (Thermal Contact Resistance)

Conduction through a joint or surface interface in intimate contact is inhibited both by the limited area of the true contact and surface contamination at the interface.

These, in combination, act as a thermal resistance to heat transmission. The heat transfer may be expressed as:

$$Q_s = H_c A\, ({}_s t_1 - {}_s t_2) \qquad (3)$$

where 'H_c' is known as the "Thermal Contact Conductance" (the inverse of the Thermal Resistance).

In bearing assemblies thermal contact resistance is manifest at the following surfaces:

(a) Shaft/Inner Ring
(b) Outer Ring/Housing
(c) Housing/Machine Base

The subject is treated in some depth in the following references: (2), (3), (4)

(II) Convection

Newton's law of cooling describes convective heat flow: viz:

$$Q_{s-f} = h_c A\, (t_s - t_f) \qquad (4)$$

'h_c' the "heat transfer coefficient," sometimes called the "film coefficient", is a complex function dependent on the geometry and temperature of the heated surfaces and the temperature flow characteristics and physical properties (viscosity, thermal conductivity and density) of the convecting fluid.

*Numbers in the text from this point refer to references.

Few analytical expressions exist for the heat transfer coefficients, empirical equations, obtained by combining experimental results with dimensional analysis, being employed. Thus the coefficients often appear as relationships between dimensionless number groups such as Nusselt (N_u), Reynolds (R_e), Grashof (G_r) and Prandtl (P_r) depending on whether free or forced convection pertains. For free convection $N_u = f(G_r, P_r)$ and for forced $N_u = f(R_e, P_r)$.

In the present analysis the following expressions for 'h_c', given by Fujii and Imura (5) and simplified by the authors, were employed.

For horizontal plates and cylinders facing upward:

$$h_c = 1{\cdot}398 \left[\frac{t_s - t_a}{X_m}\right]^{1/4} \qquad (5)$$

and for similar vertical situations:

$$h_c = 1{\cdot}452 \left[\frac{t_s - t_a}{X_h}\right]^{1/4} \qquad (6)$$

No completely reliable expressions for heat transfer coefficients between bearing components and lubricant could be found by the authors, although expressions are given by Bjordlund and Kays (6) and Gazley (7) pertaining to concentric cylinders. The existence of the rollers and cage between the bearing rings, however, tends to negate any analogy.

An expression used by Harris pertaining to heat flow across a flat plate, although of limited accuracy, was finally used in the present analysis, viz:

$$h_c = 0{\cdot}332 \frac{k}{X} R_e^{1/2} P_r^{1/3} \qquad (7)$$

Characteristic terms in the previous equation were obtained as suggested by Harris (8).

The following expressions for additional heat transfer coefficients were employed additionally in the present analysis.

(a) For a rotating cylinder in air (after Dropkin and Carmi (9))

$$\frac{h\,D}{k} = N_u = C_v R_e^{0.7} \qquad (8)$$

$C_v = 0{\cdot}076$ for $8000 < Re < 15000$

$C_v = 0{\cdot}073$ for $Re > 15000$

(b) For a rotating disc in air (after Oehlbeck and Erian (10))

$$h_v = C_d \cdot k \cdot \frac{\omega^{\frac{1}{2}}}{\nu} \qquad (9)$$

where the coefficient 'C_d' is mainly dependent on the geometry of the system.

(III) Radiation

Heat transfer by radiation between a small enclosed structure and a large surface may be expressed by a modified form of the Stefan/ Boltzmann law viz:

$$Q = \sigma\varepsilon A_1(T_1^4 - T_2^4) \qquad (10)$$

Values of the emmissivity 'ε' between 0·6 and 0·8 are given by Jakob and Hawkins (11).

7.2 Heat Generation

Generated heat in rolling contact bearings is dependent on several factors. Chiefly, these are rotational speed and lubricant viscosity and to a lesser extent, applied load and bearing geometry. Loading effects, however, become much more important if the bearings are pre-loaded.

Specificaly, the heat generated is a function of the bearing speed and torque. The latter however may be considered as the summation of the viscous friction torque M_o and the load dependent torque M_1.

The following empirical equations were produced by Palmgren (12) for these torques, ie:

$$M_o = f_o\,(\nu n)^{2/3}\, D_m^{\,3} \times 10^{-1} \quad \text{N.m.} \qquad (11)$$

$$M_1 = f_1 . F_r . \times D_m \quad \text{N.m.} \qquad (12)$$

7.3 Distribution of Generated Heat

Based on results produced by Garnell (13), Astridge and Smith (14) and work of the authors, the following distribution of generated heat was incorporated into the present programme.

(a)	Roller Contacts at the Outer Raceway	30-40%
(b)	Roller Contacts at the Inner Raceway	30-40%
(c)	Roller Contacts in the Cage Pockets	8-12%
(d)	Cage Contacts at the Land Riding Ring	8-12%
(e)	Viscous Churning of Lubricant	8-12%
(f)	Roller Guide Flange Contacts	0·1-0·8%

7.4 Temperature Prediction Technique

The so called "Heat Balance Method" was employed as the foundation to the programme. The method which is used where spacial temperature distributions are required in structures, is given in several text-books on advanced heat transfer, a good description being that given by Welty (15).

Basically the method involves the thermal equilibrium between a given point or 'node' and its surrounding nodes and is achieved by equating the total heat influx and efflux to and from the node (including any thermal energy generated at the mode).

An initial step involves the spacial selection of nodes throughout the structure, the accuracy of the analysis being dependent on both the number of nodes and their position. Fig 2 shows the nodes selected in the front bearing assembly together with the measured and predicted nodal temperatures under the particular conditions of the test.

As a second step the "Heat Balance Method" is applied to each node, all modes of heat transfer being considered. For a bearing assembly these may be typically delineated as follows:

(a) Convective heat transfer from outer surface of the housing to the environment.
(b) Radiation of heat from the outer housing surface to the surroundings.
(c) Conductive heat transfer from the housing base to the foundations.
(d) Conductive heat transfer from the bearing outer ring to the housing.
(e) Conductive heat transfer from the bearing inner ring to the shaft.
(f) Axial heat transfer by conduction along the shaft including extraneous heat inputs outside the bearing system proper.
(g) Convective heat transfer from the rotating shaft/fins to a surrounding fluid.

(h) Convective heat transfer from the bearing components to surrounding fluid/fluids inside the housing.
(i) Heat generation produced between surfaces in relative motion ie roller contacts with bearing raceways, ring shoulders and cage pockets; cage contract with ring lips; together with heat generation from viscous churning.

As an illustration of the method consider Fig. 2 as a typical bearing system with the following arbitary selection of nodal points:

Node 1 - Air surrounding housing - temperature 't_1'
Node 2 - Outer surface of the housing - temperature 't_2'
Node 3 - Inner surface of the housing - temperature 't_3'
Node 4 - Bottom surface of the housing - temperature 't_4'

Applying the "Heat Balance Method" to Node '2' gives:

$$Q_{3-2} - Q_{2-4} - Q_{2-1} = 0 \qquad (13)$$

(For convenience it is assumed that the heat influx to Node 2 is positive).

'Q'_{3-2} and 'Q'_{2-4} illustrate conductive heat transfer from Node '3' to Node '2', and Node '2' to Node '4' respectively, whilst 'Q'_{2-1} illustrates convective and radiative heat transfer from Node '2' to Node '1'.

Equations (2), (4), and (5) and (10) when simplified and applied to these nodes yield:

$$Q_{3-2} = C_1(t_3-t_2) \qquad (14)$$

$$Q_{2-4} = C_2(t_2-t_4) \qquad (15)$$

$$Q_{2-1} = C_3(t_2-t_1)^{1.25} + C_4((t_2+273{\cdot}15)^4-(t_1+273{\cdot}15)^4) \qquad (16)$$

Substituting equations (14), (15) and (16) into equation (13) gives:

$$C_1(t_3-t_1)-C_2(t_2-t_4)-C_3(t_2-t_1)^{1.25}-C_4((t_2+273{\cdot}15)^4-(t_1+273{\cdot}15)^4) = 0 \qquad (17)$$

This final equation (17) is therefore the result of applying the "Heat Balance Method" to Node 2 for the specified conditions and illustrates a typical nodal equation.

It is obvious from the foregoing that similar equations will pertain for each nodal point giving a system of non-linear equations to be solved whose number is governed by the number of nodes selected.

The third and final step of the process is to obtain a simultaneous solution to the set of non-linear equations erected, which will then represent the predicted nodal temperatures. This was accomplished by use of the computer programme briefly described hereunder.

8. THE COMPUTER PROGRAMME.

8.1 Programme Capability

At its present stage of development the computer programme has the following capability.

(a) Prediction of spacial temperature distribution at twenty nodes; these including bearing raceways, rollers, cage, housing, shaft and lubricant bath temperatures.
(b) Calculation of lubricant viscosity at the operating temperature of the oil bath.
(c) Reactive bearing torque and total heat generated.

8.2 Programme Description

The computer programme was derived from a "Fortran" subroutine given by Powell (16). The package consists of hybrid solution method combining the "Newton Raphson" method and the so-called "Method of Steepest Descent". The former provides for the linearisation of the non-linear equations whilst the latter ensures a smooth and rapid convergence. Writing equation (17) in the form RC(1) then the remaining heat balance equations may be written RC(2), RC(3).....RC(N).

The method of solution is iterative and requires an initally guessed input for the nodal temperatures. The computer routine then calculates the residuals RC(I), these approaching zero as iteration proceeds. On reaching a specified convergence criterion, programme iteration ceases, the computed solutions being then obtained as a final printout.

A monitor sub-routine programme is incorporated in the package which displays current nodal temperatures and residuals in print-out format, thereby enabling the convergence rate of the master programme to be studied. This optimises computer time utilisation and checks out any programme errors as iteration proceeds.

9. DISCUSSION OF RESULTS

9.1 Theoretically Predicted Results

Fig. 5 shows the relationship between the total generated heat (including any external input) and the total heat dissipated through heat transfer, plotted against the mean operating temperature for the two

test oils, an SAE 30 and an SAE 50. A corresponding ordinate for the friction torque has also been included. The condition is for a fixed load of 2000 N at an operating speed of 4000 r.p.m.

Points of interception of the 'Heat Generation' and 'Heat Dissipation' curves give thermal equilibrium and indicate both the relevant temperature and friction torque for this condition.

It is immediately obvious that the choice of the thinner oil would result, as is to be expected, in a lower operating temperature and reduced power loss in the bearing unit and shows the advantage of the use of a thinner oil. Values of oil film thickness computed from Elasto-Hydrodynamic theory showed an insignificant difference between the two oils. It is to be appreciated that a lower operating temperature infers increased oil change periods. Fig. 5 shows the importance of an accurate prediction of heat dissipation rate from the unit. If an underestimation of heat dissipation rate is made, there is an apparent anomaly in that the predicted temperature is greater than the experimental, whilst the corresponding friction torque is less.

This anomaly is readily explained, however, on the basis of the high non-linearity between bearing temperature and lubricant viscosity. If the heat dissipation is underestimated in the programme, the predicted bearing temperature will obviously be higher, giving a lower operating viscosity. Since the friction torque equation used in the programme itself contains a viscosity term, the result will be a lower predicted friction torque than that measured experimentally.

Apparently this anomaly was experienced by Schwartz (17), the experimental and theoretical findings reported in his paper giving a similar contradiction in the two parameters.

The effect was demonstrated, somewhat dramatically for the authors, during early development work on the programme. In normal running, after thermal equilibrium is reached, an appreciable amount of heat is conducted out of the bearing from the housing base to the bedplate. This was initially underestimated in the earlier programmes the resultant temperatures being, in certain cases, almost 50% higher than those experimentally measured, whilst the calculated torques from the programme were unexpectedly less than those measured on test.

The anomaly was finally resolved when thermocouples were placed at the base of the housing. These gave a true picture of the extent of the conduction heat transfer. It is to be inferred, therefore, in the light of this, that close attention to foundation conduction is highly relevant when assaying thermal problems in bolted down bearing housings.

A further important aspect, found when the programme had finally produced close correlation with the experimentally measured temperatures, was that roller temperatures predicted by the programme were some 15%-20% higher than those predicted at the inner ring. Since roller temperatures were not experimentally measured in the test rig, current literature was investigated with a view to producing some substantiation of this result. Confirmation was found in experimental results obtained by Norlander and Stackling (18) who measured element temperatures some 18% higher than inner ring temperatures with deep-groove ball bearings under similar operating conditions. It is possible that, in addition to viscous shear in the pocket oil film, the elements experience some rubbing against the cage from centrifugal force on the clearance side of the bearing rings, though it is appreciated that this effect depends on cage geometry and operating clearance. The fact that roller skidding had been measured in this area in previous rig trials lends some credence to this possibility.

9.2 Experimental Inferences

The effect of the housing shape and heat dissipation potential is illustrated in the asymmetrical experimental temperature distribution about the horizontal centre line in Fig. 2.

This could not be attributed to the direction of the load line since the same effect had been noted by the authors who, in earlier work on the rig, applied loads up to 22500 N, in the opposite direction, on the same bearing unit, using a hydraulic cylinder. The oil bath itself, clearly, does not transfer heat from the outer ring since its own temperature, as shown in Fig. 2, approximates to that of the outer ring in this area.

In the light of what has already been discussed on the influence of conductive heat transfer through the bearing housing base it is to be concluded that this is the controlling factor; the base conductive heat transfer outweighing surface convective heat transfer to produce the asymmetrical temperature profile. This was confirmed on measuring temperatures on the inverted hydrostatic bearing at the rear of the ring, the same asymmetry being produced in the ring irrespective of oil flow between the hydrostatic bearing surfaces. This conclusion is reinforced on observing the significant temperature gradients in the lower part of the housing (Fig. 2.). Calculations based on these values showed that some 45% of the total heat generated is dissipated in this way.

Similar calculations showed a further 28% of generated heat dissipated through the rotating shaft/fin assembly.

10. CONCLUSIONS

10.1 General Programme Utilisation

It has been demonstrated that a viable computer programme based on analytical heat transfer techniques may be constructed which is capable of predicting spacial temperature distributions in rolling contact bearing assemblies and that the predicted results yield close correlation with experimentally measured values.

From the standpoint of the industrial user/designer the programme capability can be utilised in several ways:

(a) Optimum lubricant selection, commensurate with the bearing duty, may be obtained at the design stage to ensure minimum power loss.
(b) For a lubricant already specified the designer can quantify any critical thermal situation from a knowledge of both the spacial distribution of temperature and the prediction of any localised temperature. This is of particular importance when temperature effects induce dimensional changes.
(c) Since different bearing geometries may be catered for in the programme, the designer can study the effect of differing housing configurations on spacial temperature distribution and heat dissipation. Foundation effects can also be catered for.
(d) For bearing assemblies already in operation the industrial user can assess potential energy saving through lubricant viscosity changes, together with the effects of extended oil change periods when bearing temperatures have been lowered.

10.2 Specific Design Considerations

If thermal analysis indicates that bearing cooling is necessary, particular attention should be paid to which components should be specifically cooled.

External cooling of the housing will, in general, reduce dimensions between inner and outer rings if the shaft temperature itself is not appreciably affected. The resulting reduction in element clearances may produce an increase in power loss tending to invoke a thermal spiral. In extreme cases this may produce bearing seizure.

Since it has been shown that a significant percentage of heat is conducted through the housing base to the foundations, excessive conduction in this area may produce similar effects to those outlined above. Conversely any condition increasing insulation at the joint face will tend to retard these effects.

Good surface contact at the interface is important. Variations in surface flatness may produce large variations in local contact resistance with a concomitant variation in conductive heat transfer. Thermal distortions arising from this effect may be passed to the bearing with a consequent reduction in its useful life.

Shaft cooling will undoubtedly increase radial clearances between rollers and rings of plain roller bearings. However, in pre-loaded assemblies axial contraction of the shaft may increase the pre-load, dependent on the mounting arrangement, particularly in taper-roller bearings with "indirect" mounting. Such a situation may incur high local temperatures between rollers and guide flanges. Overcooling of a shaft can, additionally, initiate inner ring creep or even slippage.

It is seen from the foregoing that variations of temperature within a bearing assembly are capable of producing exceedingly complex effects and this highlights the importance, to the designer, of having a thermal analysis programme capable of predicting local temperatures.

Such a programme, it may be inferred, not only mitigates any propensity towards premature mechanical failure initiated from thermal sources but, from the standpoint of basic design and subsequent in-service duty, provides a further step towards an optimum level of total energy conservation.

The economic implications of such an approach, particularly in the long-term aspect, are deemed worthy of consideration.

ACKNOWLEDGEMENTS

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NOTATION.

a	-	Length of larger side of a rectangular section	(m)
A	-	Area of a surface normal to heat flow	(m^2)
$A_{1,2}$	-	Area of surface 1, 2	(m^2)
b	-	Length of smaller side of rectangular section	(m)
C_{1234}	-	Constants in the "Heat balance equations"	
$C_{v,h}$	-	Constants in the equations for the heat transfer coefficients	
D	-	Diameter of shaft	(m)
D_m	-	Mean diameter of bearing $D_m = \frac{D_o + D_i}{2}$	(m)
D_o	-	Outer diameter of bearing	(m)
D_i	-	Inner diameter of bearing	(m)
f	-	Geometrical factor $f = \frac{a}{b}$	
$f_{0,1}$	-	Friction torque coefficients, given by bearing manufacturers	
Fr	-	Radial load	(N)
$h_{c,v}$	-	Heat transfer coefficient	($W/m^2{}^oC$)
H_{min}	-	Minimum oil film thickness	(μm)
H_c	-	Thermal contact conductance	($W/m^2{}^oC$)
i,j	-	Subscript referring to Node i and j	
k	-	Thermal conductivity solid or fluid	(W/m^oC)
$k_{1,2}$	-	Constants	
L	-	Length of heat transfer path	(m)
M	-	Total bearing torque	(N.m)
M_2	-	Viscous friction torque	(N.m)

M_l	-	Load dependent torque	(N.m)
n	-	Shaft rotational speed	(r.p.m.)
N	-	Number of temperature Nodes	
Nu	-	Nusselt Number $Nu = \frac{h_c X}{k}$, $\frac{h_v D}{k}$	
Q	-	Heat flowing from a surface to a fluid	(W)
Q_e	-	External heat input to bearing assembly	(W)
Q_{i-j}	-	Heat conducted from surface 'i' to surface 'j'	(W)
Q_{Gen}	-	Heat generated in the bearing	(W)
Q_s	-	Heat flowing through contacting surfaces	(W)
R	-	Radium of housing bore	(m)
RC(1)	-	Residuals, in computer programme I = 1,2.....N	
R_e	-	Reynolds number $R_e = \frac{w D}{\nu}$, $R_e = \frac{v X}{\nu}$	
R_i	-	Inner radius of bearing ring	(m)
R_o	-	Outer radius of bearing ring	(m)
$t_{i,j}$	-	Temperature Node 'i' and Node 'j'	(^oC)
t_s	-	Surface temperature	(^oC)
s^t_{1-2}	-	Temperature of surfaces 1 and 2	(^oC)
$t_{f,a}$	-	Fluid temperature and air temperature	(^oC)
T_{i-j}	-	Absolute temperatures of surfaces 'i' and 'j'	(k)
v	-	Linear velocity	(m/s)
ω	-	Angular velocity	(rd/s)
X	-	Characteristic dimension of a heat transfer path e.g. width, length or height of a surface or diameter of a cylinder	(m)

ε - Effective "emissivity" between surface 'i' and 'j'

σ - Stefan/Boltzmann constant = $5{\cdot}76 \times 10^{-8}$ $W/m^2\ K^4$

ν - Kinematic viscosity of a fluid (mm^2/s)

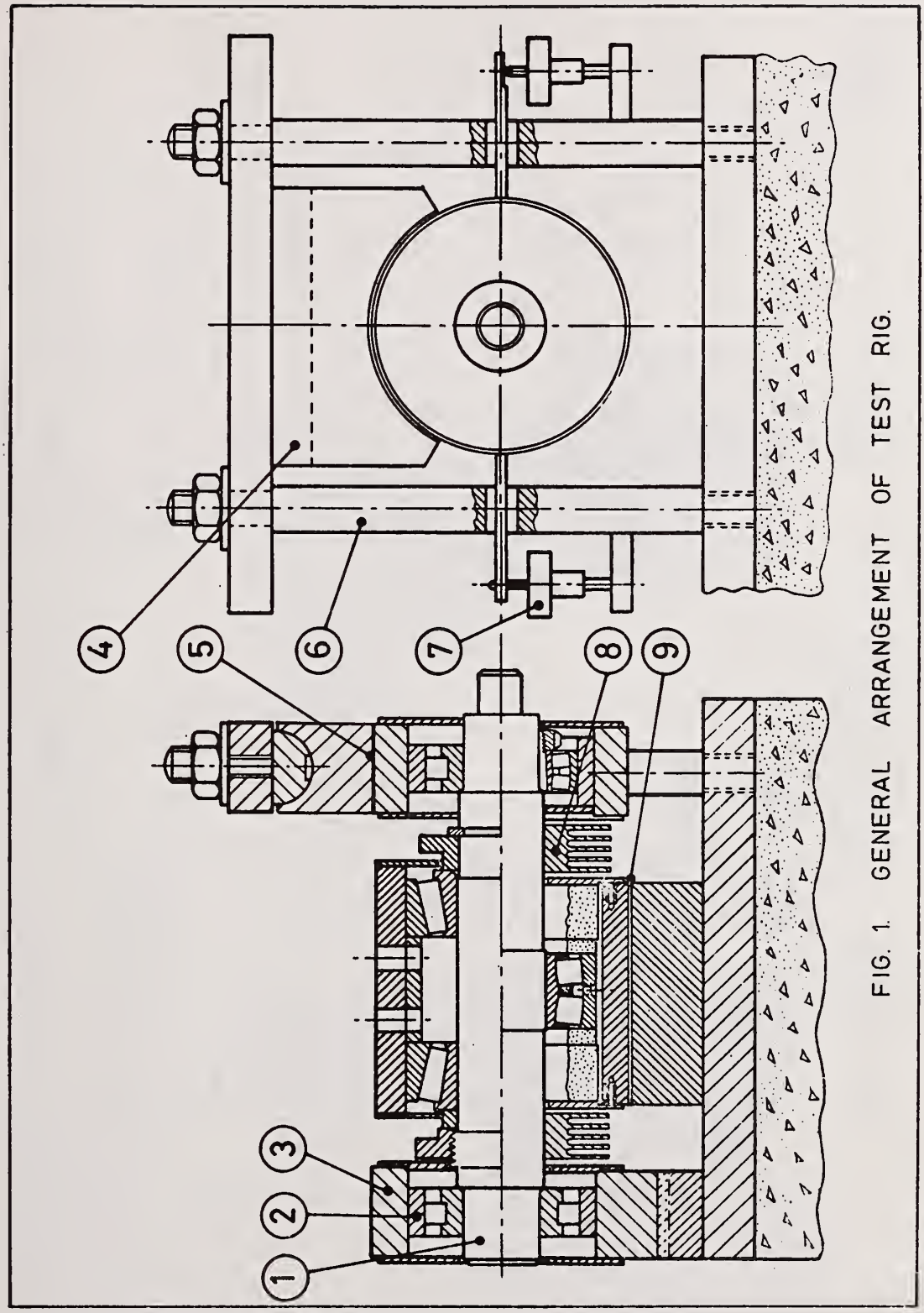

FIG. 1. GENERAL ARRANGEMENT OF TEST RIG.

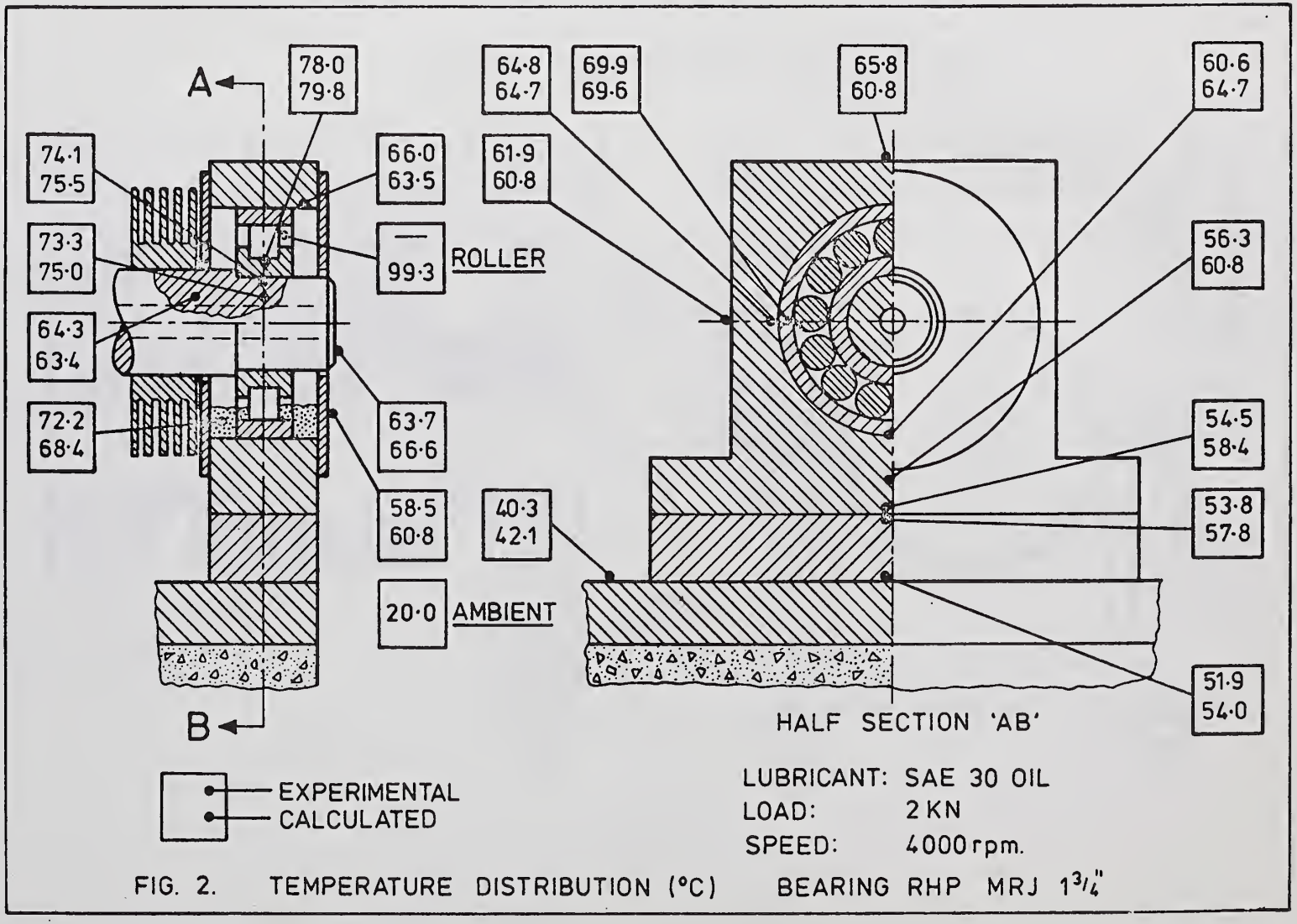

FIG. 2. TEMPERATURE DISTRIBUTION (°C) BEARING RHP MRJ $1^{3}/_{4}$"

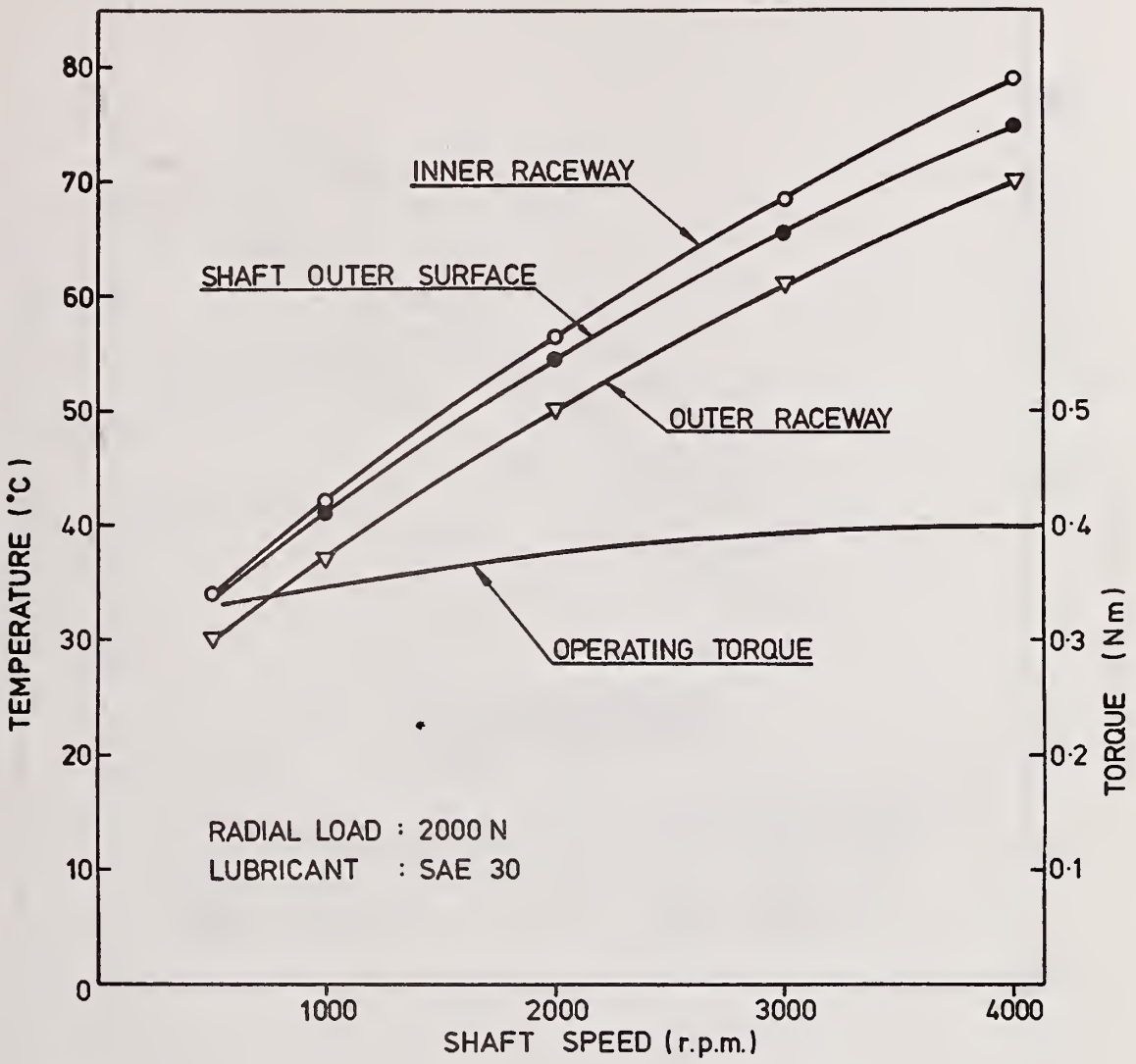

FIG. 3 TEMPERATURE AND TORQUE VARIATION WITH SPEED

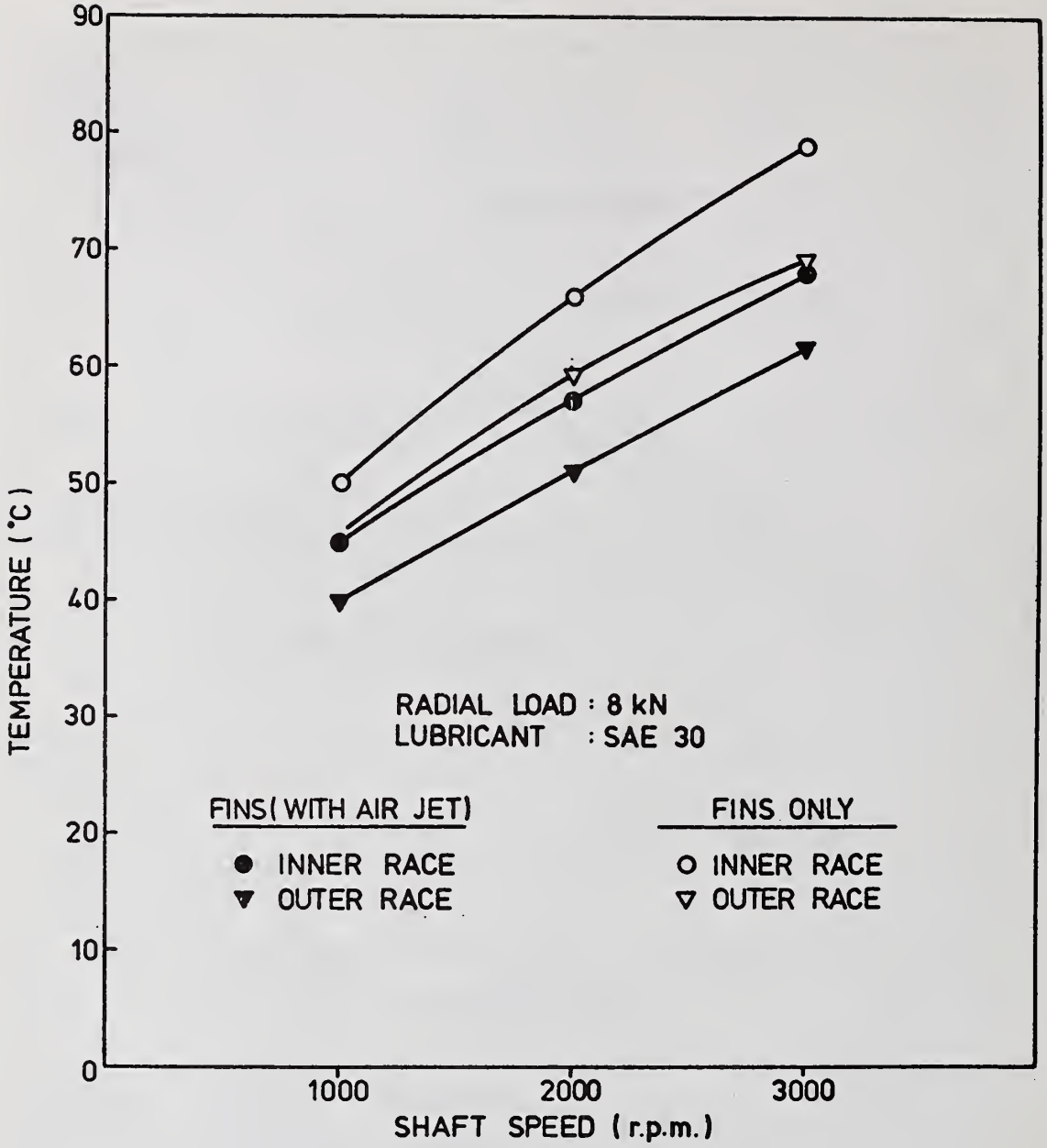

FIG. 4. THE EFFECT OF AIR COOLING ON BEARING TEMPERATURE BEARING RMJ 1¾"

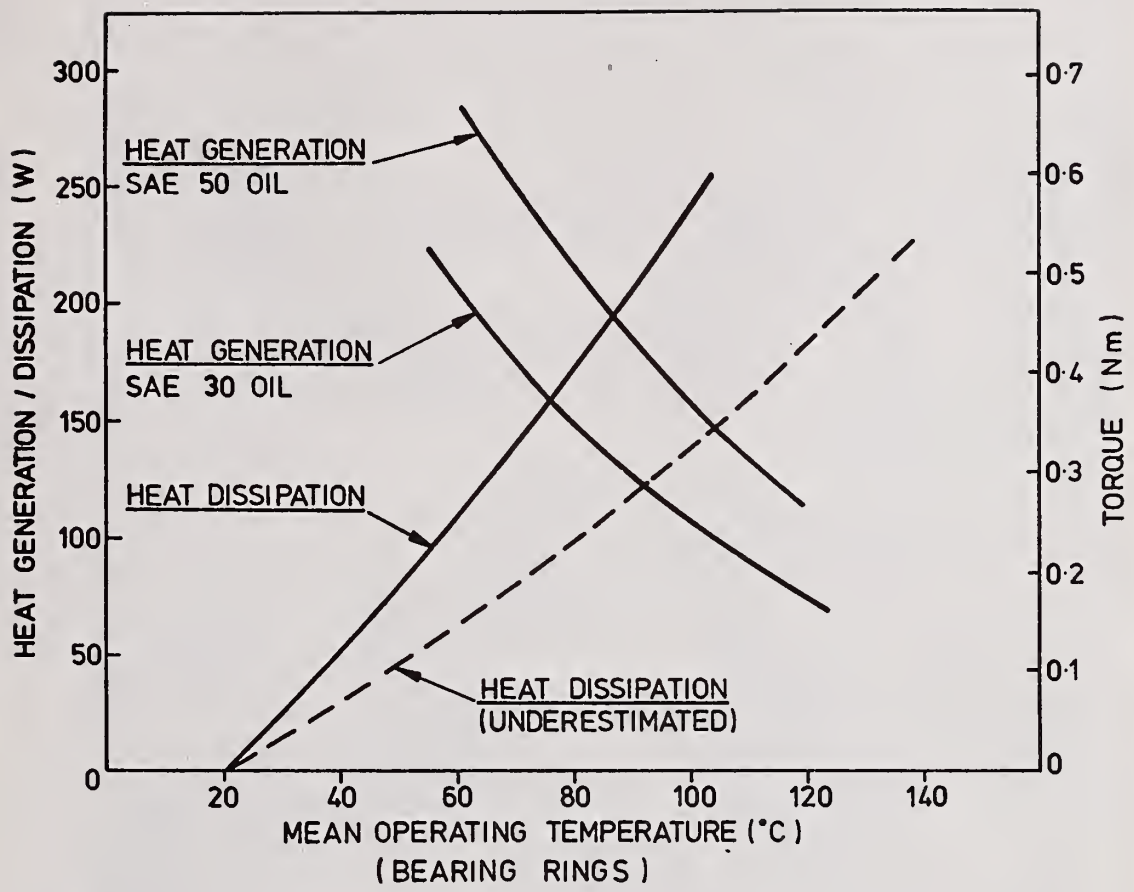

FIG. 5. THERMAL BALANCE: BEARING RMJ 1¾"
SPEED: 4000 R.P.M. LOAD: 2000N

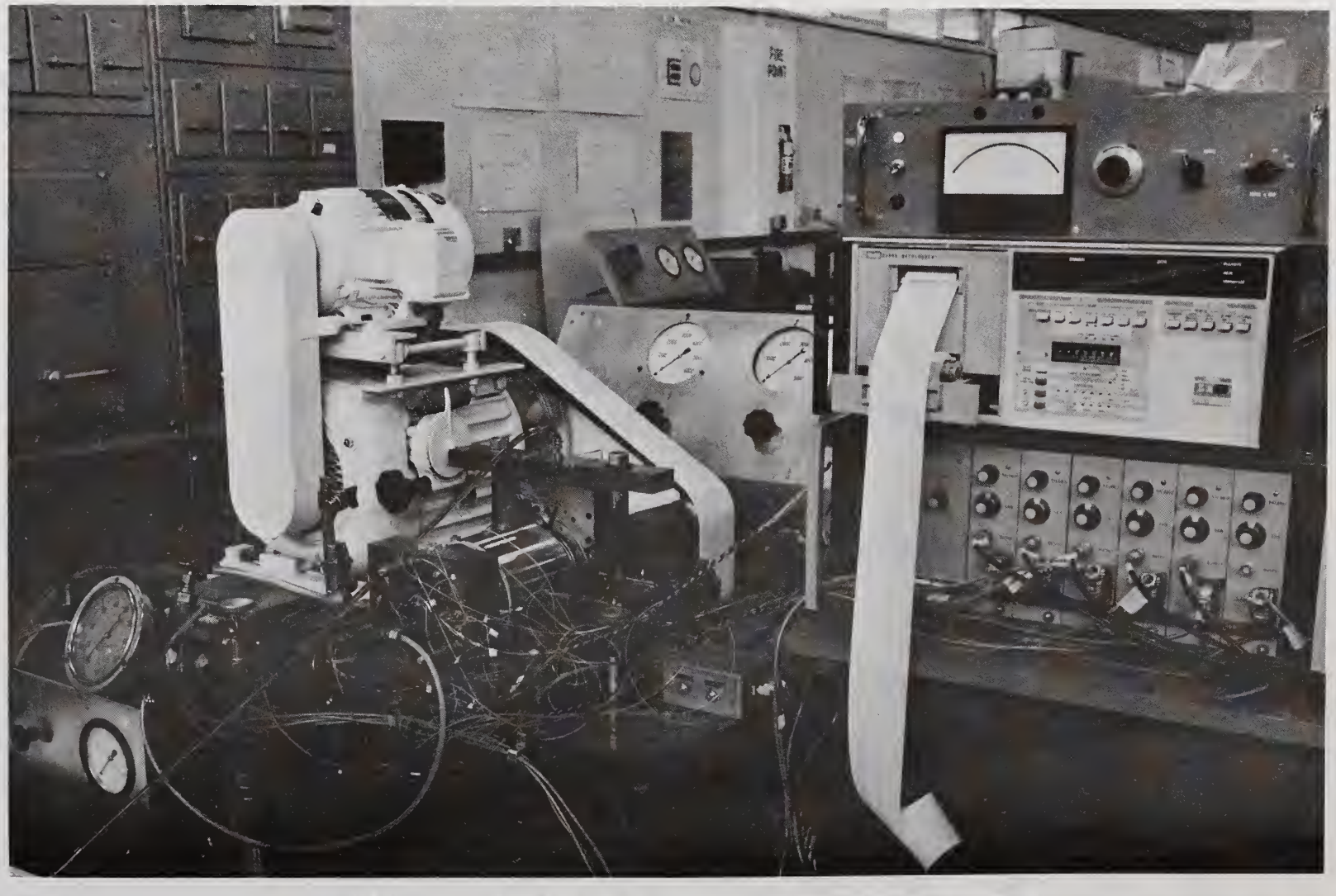

PLATE 1. GENERAL VIEW OF TEST RIG AND INSTRUMENTATION

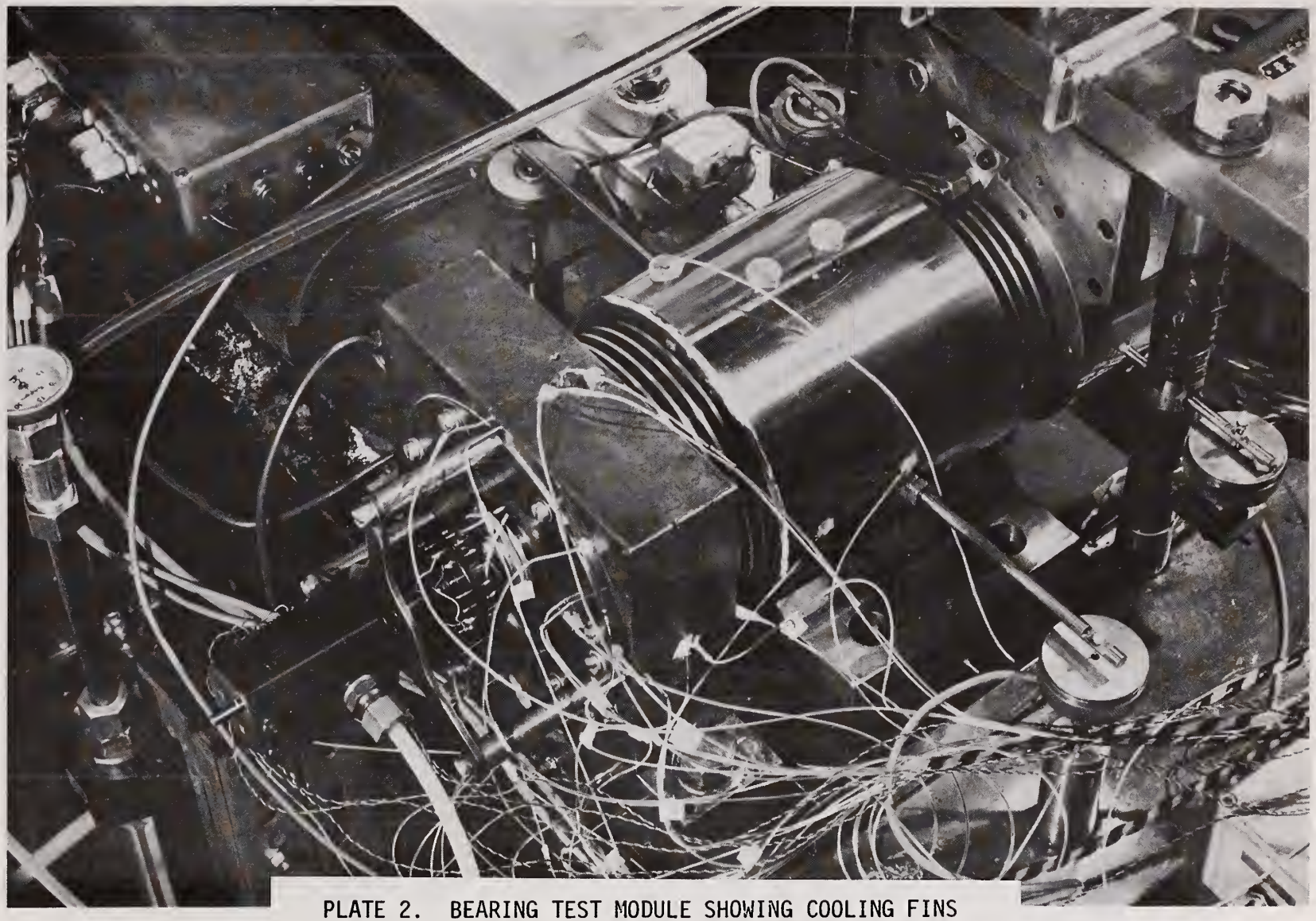

PLATE 2. BEARING TEST MODULE SHOWING COOLING FINS

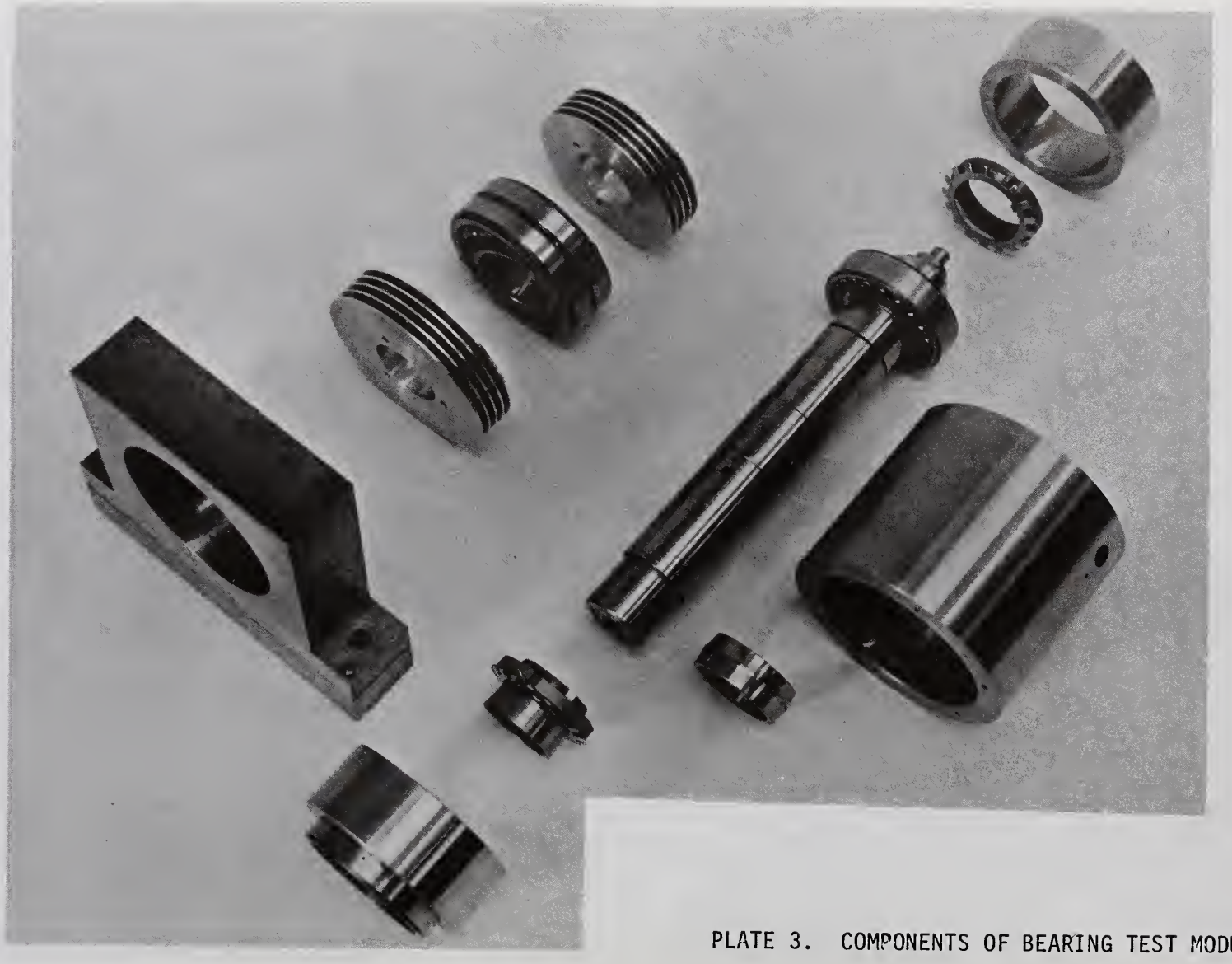

PLATE 3. COMPONENTS OF BEARING TEST MODULE

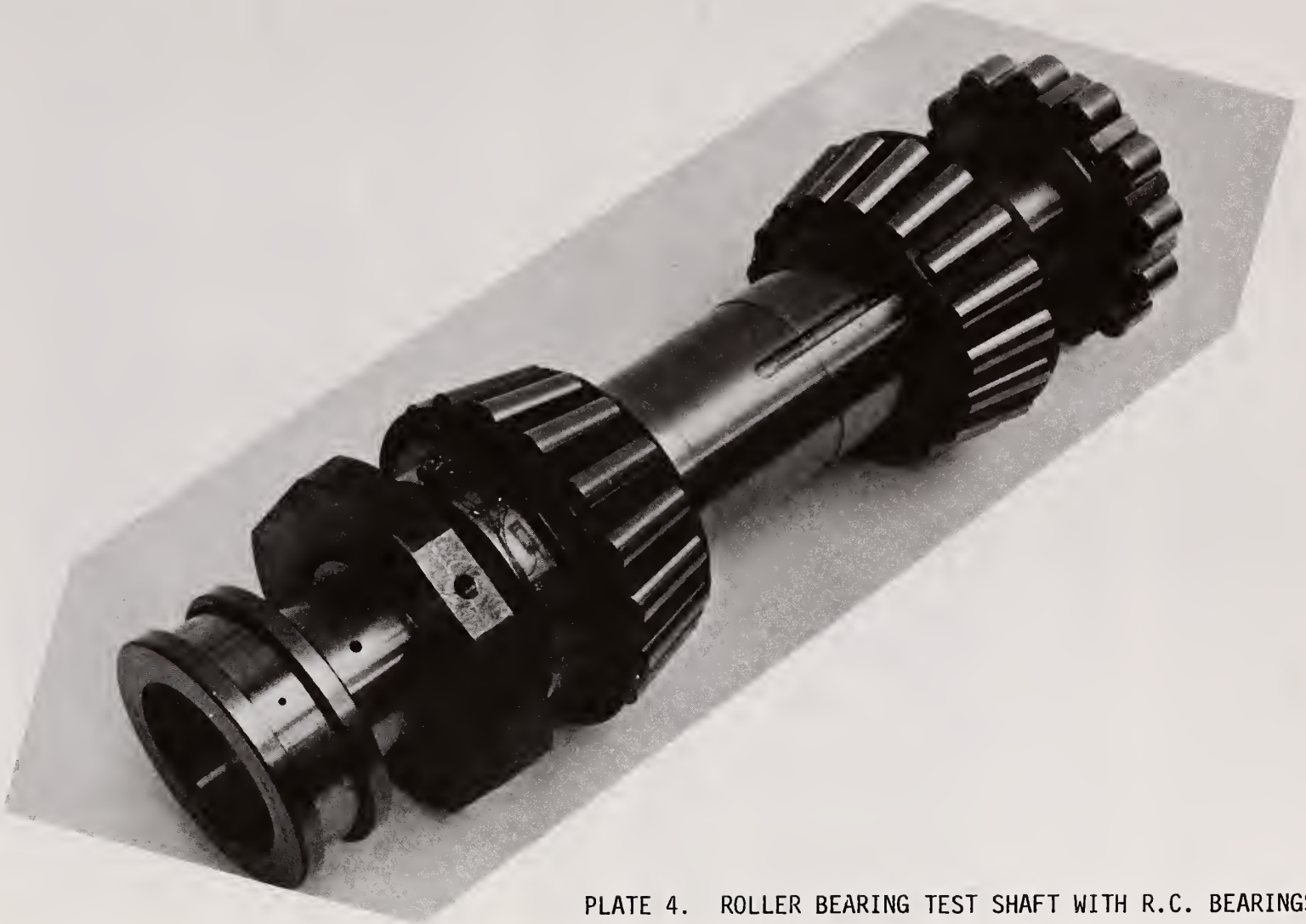

PLATE 4. ROLLER BEARING TEST SHAFT WITH R.C. BEARINGS

THE INFLUENCE OF FILTRATION ON ROLLING ELEMENT BEARING LIFE

R. Bhachu and R. Sayles
Imperial College
London, SW7 2BT, England

P. B. Macpherson
Westland Helicopters Limited
Yeovil, England

Abstract: Using a gear machine to generate debris, which had been verified by Ferrographic analysis as being representative of that found in helicopter gearboxes, contaminated oil was passed through filters of different sizes before being fed into a parallel roller bearing fatigue machine. In-line particle counting monitored the debris content of the oil which was based on a helicopter type of lubricant. Filter sizes ranged between 1 and 40 μm absolute ratings and sub-micronic extraction was achieved by using electro-magnetic filtration. Bearing fatigue tests were run, under constant operating conditions, for all filter ratings and Weibull lines were drawn based on a minimum sample size of 10 failures. From these a relationship between filter rating and fatigue life was established. The experimental program is described and results discussed.

Key words: Filtration; gearboxes; helicopter transmission; pitting; rolling element bearings; rolling fatigue; spalling.

Introduction: Observations carried out during the last 20 years provide strong evidence to suggest that indentations formed by the rolling-in of debris were responsible for many of the early rolling element bearing failures experienced in helicopter gearboxes. During this period effective steps were taken to improve the cleanliness of bearing steels and this resulted in greatly increased rolling fatigue lives. It seemed reasonable to suppose that a debris indentation could impair fatigue properties just as much as a non-metallic inclusion yet, until recent years, such obviously damaging defects have been ignored.

It was not until the work described in (1) was published that active interest was directed towards the influence of filtration on bearing lives. A more comprehensive study (2) confirmed the importance of filtration. The present authors considered that the morphology of the indentations to be of such importance that they elected to study the effect of real debris, as opposed to artificial as used in (1) and (2), on rolling fatigue lives.

Current practice is to fit either 40 or 25 μm filters to helicopter main gearboxes. Sufficient evidence was available to suggest that 3 μm filtration would improve bearing performance to such an extent that little purpose would be served in extending the proposed study to finer levels of filtration. On the other hand, the oil film generated between opposing asperities in a typical EHD contact is about 0.012 μm and so, for complete protection, the aim could well be to incorporate sub-micronic filtration.

From practical considerations, 3 μm absolute rating cartridge type filters could be fitted retrospectively with a minimum of work, even using existing filter housings. Sub-micronic filtration would involve the regular polishing of the lubricating oil as is sometimes the practice with hydraulic systems. Centrifugal type filters, being limited by size and speed if fitted to a helicopter gearbox, would remove particles down to the equivalent of 2 μm size but care would have to be exercised in the design to prevent mechanical damage to the long chain molecules present in the oil. Centrifugal filters could only be considered for new gearbox designs but what could be a strong point in their favour would be water and air extraction. The water content in synthetic oils tends to be surprisingly high (3) and the prevention of fretting demands a minimum amount of air in circulation (4).

The main objective of the experimental work described in this paper was to determine a practical filtration target for immediate application that could reasonably be expected to lead to extensions in 'Times between overhaul' (TBO's). It was also the intention to collect data for use in a subsequent theoretical exercise to be aimed at minimising the amount of debris generated within a damaging size range. It was hoped that a satisfactory explanation of the bi-modal situation, which is so often present in Weibull line presentations, along with the variation in Weibull line slopes for different operating conditions, could be established. The theoretical studies are now in hand and in the present paper the experimental programme and results obtained are described and discussed.

Apparatus: The philosophy behind the design of apparatus used was, basically, that representative helicopter type debris be continuously generated so that by filtering and monitoring the oil, known contaminant distributions were present when it was fed into a parallel roller bearing fatigue machine. Bearing lives were to be measured in terms of absolute filter ratings, and β values which are more informative, while all other variables were maintained constant. In order to minimise unprogrammed stoppages it was decided to generate debris in gear pairs by running with a helicopter type oil specially formulated to have a lower load carrying capacity than normal. This was preferable to operating a gear machine at high torques over protracted periods when, inevitably, much time would be expended in maintaining the machine.

As it was intended to retain the gear machine for general laboratory use much consideration was given to choice of gear specimens. They had to be of EN39B or similar type of steel, carburized and hardened to approximately 750 VPN after grinding. They also had to be essentially of helicopter form, so a suitable pair was designed. On reflection this appeared to be a retrograde step because, once again, we should find ourselves using unique test equipment with the consequent difficulty of correlating results with those from other laboratories. The NASA test gears did not differ overmuch from our own design so, with their agreement, their design was adopted.

It is essential that torque can be altered in a gear machine while running. Extensive experience with disc machines clearly shows that results obtained by stopping a machine to alter the torque should be treated with caution. It is the normal practice in the laboratories with which the author's are associated, to use an epicyclic system for applying torque. In the present case funds would not permit the use of an epicyclic so, again, help was sought from NASA who agreed to the use of their hydraulically loaded blade torquing design which is basically similar to the well established system used in marine work. Thus, essentially, the gear machine designed was similar to that which NASA has established over the years although it differs in lay-out and detail.

Fig. 1 shows the layout of the equipment but omits the bearing fatigue machine which is of conventional design. Contaminated oil is fed through a previously calibrated filter into the bearing machine. In-line particle counting is provided for continuous monitoring from positions down and upstream of the filter. Problems associated with air bubbles had been anticipated but by using a funnel shaped settling tank all air was liberated and no bubbles were, in fact, observed in the HIAC system. The magnetic filter to be seen to the left in Fig.1 was used for sub-micronic particle extraction and for the rapid polishing of the oil when required. The cartridge type filters were of absolute ratings 40, 25, 8, 2 and 1 μm. The test oil circuit is shown in Fig. 2.

An accelerometer, centrally located between the two test bearings, successfully registered the onset of spalling and the machine was automatically shut down on reaching a pre-determined vibration amplitude. All previous attempts to monitor line contact failures with an accelerometer had proved unsuccessful so it was with considerable surprise that the system worked well in this instance. It just so happened that the accelerometer had been sited immediately over the loading bearing yoke and, fortuitously, this was acting as a mechanical amplifier. Repositioning the accelerometer rendered it useless so throughout the testing both test bearings had to be removed and examined to determine which one had failed.

Appendices 1,2 and 3 describe the test bearings, gear steel and

bearing steel respectively.

Filter Ratings: AC Fine Test Dust (ACFTD) is universally used as a fluid contaminant for determining the effectiveness of a filter because it has a known particle size distribution. However, these dust particles bear little resemblance to those generated in a gearbox and thus filter ratings are a standard only and do not necessarily relate directly to practical situations. It has to be emphasised that a filter rated at 2 μm will not prevent the passage of all particles sized 2 and above.

Every filter has a characteristic curve of efficiency in terms of particle size as illustrated in Fig. 3, where the efficiency η for each particle of radius a is defined as,

$$\eta\ (a) = \frac{n_c(a)}{n_i(a)} = 1 - \frac{n_e(a)}{n_i(a)}$$

$n_c(a)$ = number of particles of size a per unit vol. captured by the field
$n_i(a)$ = number of particles at filter inlet
$n_e(a)$ = number of particles at filter exit

Fig. 3 also shows how absolute filter performance relates to the real one.

In many respects the β ratio, developed by Fitch and his colleagues (6) and (7) as a filter model to define its performance, is more informative than the absolute rating.

$$\beta = \frac{n_i(a > a_o)}{n_e(a > a_o)}$$

This is the ratio of the number of particles per unit volume of size greater than a_o at the inlet to the number at the exit. Thus the higher the β value the better the filtration. This ratio led to the β_{10} model (8). β curves are established for the filters by plotting on special semi-log paper and then each curve is specified by its β_{10} value, i.e. the β values for 10 μm particles. It is to be noted that $\beta(a_c)$ can also be determined from the particle frequency distribution function.

It is obviously convenient to use a single parameter to define performance but the Authors are by no means convinced that the β ratio, based on ACFTD calibrations fulfils this function any better than a c.ℓ. a. (RA) value describes the topography of a surface. It seems clear that in both cases the single parameter is useful when comparing 'Like with Like', but its usefulness is not so clear in other cases.

Parameters such as collector size, porosity, material, flow rate, viscosity, length, particle concentration etc. must all influence filter performance. The Authors have found the use of discriminant functions useful in determining the relative importance of groups of variables and are currently applying such techniques as part of a detailed theoretical study into many aspects relating to filtration and the damaging influence of debris. For this reason absolute ratings are used in the present paper and reference to β values is reserved for a future occasion. Meanwhile it is to be noted that the β_{75} rating, i.e. the particle size at which $\beta = 75$, is very close to the absolute rating. Thus an absolute rating of 40 μm closely approximates to $\beta_{40} \geq 75$.

Results: Unless otherwise stated, tests were run under the following conditions:

Bearing speed 5,000 r.p.m.
Applied load 2,957 N (665 lbs f)
Max. contact stress between rollers and inner race, 2.82 GPa (408,900 lbs/in^2
Bulk oil temperature 70^{o}C (158^{o}F)
Calculated central oil film thickness, 0.576 μm (22.68 μ ins)
Mean calculated λ ratio, 1.52
Catalogue life of bearing under these conditions 13 hours

Tests were terminated on detection of a pit measuring 0.4 to 0.6 mm diameter.

S/N Curve: Initially tests were run with a 3 μm filter at 3 stress levels to establish a rudimentary S/N curve from which to select an appropriate bearing load for use in the experimental programme. The curve was subsequently refined, so that it could be used for reference purposes, and is shown in Fig. 4 based on B_{50} lives.

Rolling Fatigue Lives: Tests were run under standard conditions to determine the fatigue lives for the various levels of filtration, viz. 1,3,8,25 and 40 μm absolute ratings. Sample size was such as to give a minimum of 10 failures for each series of tests and Weibull lines were drawn for all results. These lines are shown in Fig. 5 and B_{10} and B_{50} lives for the series are plotted against filter rating in Fig. 6. The results are tabulated in Table 1 and include confidence limits.

Oil Film Thickness: The influence of the oil film thickness being generated was investigated by reducing the bulk oil temperature to 30^{o}C. The increased viscosity raised the oil film thicknesses to 0.987 μm and resulted in longer life as can be seen from Table 1.

Changing Filtration Level during Test: Tests were run at 30^{o}C oil temperature with 40 μm filtration for 30 minutes before switching to

3 μm filtration at which level the bearings were run to failure. As will be seen from Table 1 the lives are substantially the same as if the test had been run with 40 μm filtration.

Post Test Examinations

1. Metallurgical: Preliminary examination of all rolling surfaces was made under low magnification (x 25) when general features were noted and nature of the failures tentatively identified. Debris indentations were revealed over all the surfaces along with occasional transverse cracks. Microhardness measurements were made across the rolling tracks and Nital-etch examination for possible grinding burns. The most interesting looking failures were selected for detailed examination when metallographic sections were prepared through failure sites to study the microstructure and to obtain further information on the failure mechanism. Fatigue failure profiles were studied by progressively grinding back and polishing across the running path.

The following failure modes were identified and classified as follows:

Transverse cracks across running path
Incipient failure at a transverse crack
Straight sided or circular pit at transverse crack
Incipient failure not associated with a transverse crack
Fatigue pit not associated with transverse crack
Fatigue pit at indentation
Extensive surface break-up near an indentation or crack

The distribution of failure classification in terms of contamination level was studied, but no overall pattern was discernible. A summary of main observations is as follows:

1) Generally, transverse cracks were found for all levels of filtration.

2) The presence of failures both with and without transverse crack association, under all levels of filtration, demonstrated that the failure mechanism was independent of filtration level.

3) Many of the failures were associated with debris indentations and surface scratches.

4) Metallographic examination in the rolling direction revealed that the transverse surface cracks penetrated perpendicularly to the surface to depths of between 0.20 and 0.75 mm.

5) Secondary cracking branching off the primary cracks was frequently observed at depths below the surface of 0.08 to 0.10 mm.

A typical example of a debris indentation initiation site crack is shown in Fig. 7. The average size of pit formed was between 0.4 to

0.6 mm diameter and 0.05 to 0.10 mm deep.

2. Surface Topography: Talysurf recordings were taken of track and roller surfaces from both damaged and undamaged areas. From these the geometry of the indentations was determined. Composite roughness values and λ ratios are set out in Table 2.

3. Roundness: 'Talyround' measurements were made of a virgin bearing inner race along with those from all suspended, i.e. unfailed, bearings. The recordings are shown in Fig. 8.

Discussion: While it is not suggested that all helicopter bearing failures result from the rolling-in of debris, the experimental results clearly imply that better performance would result from the introduction of finer filtration. It will be seen from the 90% confidence limits quoted that a large difference in filter rating is required before statistical significance can be placed on the results. The results also suggest that the fitting of fine filters to a gearbox is likely to prove of little value unless extreme care is taken to ensure that all damaging debris is removed from the gearbox prior to its initial run in a test stand. Likewise, steps must be taken to prevent the entry of contaminants into the gearbox from test stand parts such as oil coolers.

The apparent relationship of filter rating and Weibull line slope is interesting and confirms the trend noted in (9 and 2). At first sight the slope relationship would appear to be similar to that experienced at different loadings in bearing fatigue tests. Normally, as in the case of rotating bending, at high loads the scatter is much smaller and this can be related to cycles required for crack development and crack propagation. A detailed study is being made of the Weibull line slopes.

As is usual in rolling fatigue work the Weibull lines tend to display bi-modal situations. This will result from the summing of two or more failure mechanism distributions. There appears to be a connection between filter rating and the incidence of the bi-modal situation and this becomes more obvious as the state of filtration is improved. By considering the Equivalent Stress concept(which is discussed later and recorded in Table 3), it could, perhaps, be expected that the position would tend to be analogous to Reverse Bending experience. This is not, however, the case because in bending work the bi-modal situation tends to arise in the mid stress region, i.e. as a result of summing the two distributions that are so apparent at high and low stress levels.

To derive a feel for the benefits that could be expected to result from improved filtration in terms of load carrying capacity, resort was made to a concept of 'Equivalent Stress to Failure'. This is simply the stress, taken from the S/N curve, required to produce a failure with a 3 μm filter for corresponding B_{50} lives for different

filter ratings. The results, as tabulated in Table 3, indicate that contact stress limits could be doubled to achieve the same life by changing from 40 to 3 μm filtration. This is, of course, no more than a guide but should further testing confirm that such improvements are feasible then much importance will be attached to this aspect. In general terms it is not difficult to extend fatigue lives, corresponding to just below the stress endurance level, by large amounts whereas it is extremely difficult to achieve any really worthwhile increase in load carrying capacity.

The relationship between filter ratings and B_{50} fatigue lives is shown in Fig.9. Between the 3 and 40 μm filter levels $L = 77.33\mu^{-0.68}$, where μ represents filter rating. Replotting the results as in Fig.10 clearly shows the improvement in performance that can be achieved by fitting filters finer than 40 μm. It is apparent that for really worthwhile benefits the filtration level should be improved to at least 10 μm.

One of the most interesting features of the post test examinations was in the 'Talyround' recordings. With 40 μm filtration the out-of-roundness was greater than in the virgin bearing. A gradual improvement was observed with finer filtration down to the 8 μm rating and then a marked improvement between 8 and 3 μm at which point there was virtually no out-of-roundness. Below the 3 μm level the trace was similar to that of the virgin bearing. It would seem that particles smaller than 3 μm were too small to have any effect and merely passed through the contacts. Over 3 μm size produced a lapping action which in the case of 3 μm filtration improved the roundness of the race. This result tends to confirm suspicions that the size range of damaging debris is relatively small. Above a limiting size the particles will not enter the contact and below a lower limit will pass straight through. The prevention of the generation of damaging size debris through control of surface finish is currently being sought by the Authors. The Talyround results tend to substantiate the main findings that, under the conditions of the testing, there would be little point in filtering finer than a 3 μm rating.

As could reasonably be predicted for a given particle size or, more correctly, a given filter rating, the thicker the oil film generated within the contact the less the damage, but only so long as one is dealing with debris of a damaging size which, in turn, will relate to the oil film thickness. An increase in oil film thickness from 0.576 to 0.987 μm brought about an increase in fatigue life of some 40% for the 3 μm rating whereas it was only 10% with a 25 μm filter. It would appear that an equivalent to the well established λ ratio is relevant to relate debris size to surface roughness. This aspect is now being considered but, as in the case of λ, it is necessary to replace the 'Composite Roughness' with something more meaningful and to establish a relationship between particle size as recorded and its deformed thickness.

No metallurgical reason could be found to account for those very early failures which tended to reduce B_{10} lives quite markedly. In general it was found that the depth of the primary cracks exceeded that of the estimated maximum shear stress by a considerable margin. However secondary cracking did arise at depths between 0.08 and 0.10 mm and these dimensions do correspond with the depth of maximum shear stress. As usual, subsequent propagation was in the rolling direction and parallel to the surface, to lead to breakout of the crack and flake dislodgement to form a fatigue pit.

The influence of filter size on the rate of generation of particles greater than 2.5 μm is shown in Fig. 11. Presumably some of the larger particles will break up into smaller ones and this will be a function of running time.

Conclusions: The experimental work described in this paper supports the evidence becoming available from helicopter trials, and other relevant experience, that the replacing of 40 or 25 μm filters by units rated at 3 μm absolute is to be recommended for helicopter gearbox installations. Such action should lead to improved reliability, longer periods between overhaul, cheaper overhauls and consequent reductions in ownership costs. Times between oil changes, where relevant, should be substantially increased. These improvements in performance can, however, only be realised if the gearbox manufacturers ensure that primary damage has not already been initiated before the gearbox is installed in a helicopter.

It could,possibly, be found in future work that filtration down to submicronic levels is worthwhile. If so, then regular polishing of the oil at pre-determined intervals would be indicated. Such could, however, possibly result in the situation of producing an ultra clean oil that would not lubricate as a direct result of contaminant extraction. The role played by contaminants in lubrication is currently being investigated.

No matter how fine the filtration it is not going to prevent freshly generated debris from entering contacts. It is, accordingly, necessary to take steps to ensure that, as far as is practicable, the debris being generated is of a non-damaging size. Results obtained from the experimental programme described in this paper suggest that an approach along these lines is a realistic one because the damaging size range is relatively narrow.

In conclusion, it can fairly be stated that one of the most encouraging features of this work is the generally growing realisation that debris indentations are just as damaging as non-metallic inclusions and that fine filtration is essential just as in the use of clean steels in bearing and gear manufacture.

Acknowledgements: Reference should be made to the unusually large degree of co-operation that has been extended to the Authors during the course of running the filtration programme. Assistance from the following organisations is gratefully acknowledged; NASA (Lewis), Mobil Oil Company, R.H.P. Bearings and Pall Filters.

The Authors thank the U.S. Office of Naval Research and the U.K. Ministry of Defence for having funded the project and, along with Westland Helicopters Limited, permission to publish.

Test No.	Test Filter Absolute Rating (micron)	Experimental Life (millions of stress cycles)				Weibull Slope
		B_{10} Life	90% Confidence Limits	B_{50} Life	90% Confidence Limits	
*1	40	1.497	1.00 - 2.02	2.076	1.89 - 2.29	5.76
2	25	2.457	2.04 - 2.95	3.002	2.91 - 3.09	9.40
3	8	4.470	3.44 - 5.81	5.849	5.44 - 6.33	7.00
4	3	8.036	5.54 - 11.64	12.022	10.70 -13.46	4.68
5	1	6.535	3.60 - 11.77	12.427	9.94 -15.54	2.93
6	Magnetic	4.975	2.93 - 8.45	10.013	8.31 -12.01	3.21
7	40	1.795	-	3.283	-	3.12
8	3	9.252	-	16.233	-	3.35
9	40/3	1.723	-	3.050	-	3.30

*Test results 1 to 6 relate to calculated film thickness of 0.576 micron and results 7-9 to 0.987 micron film thickness.

Table 1

Specimen	Composite Roughness (micron)	Calculated Film Thickness (micron)	λ
Virgin Bearing	0.38	0.576	1.52
40 micron	0.41	0.576	1.41
25 micron	0.36	0.576	1.60
8 micron	0.32	0.576	1.80
3 micron	0.26	0.576	2.22
1 micron	0.22	0.576	2.62
Magnetic	0.20	0.576	2.88

Table 2

Filter (micron)	Experimental B_{50} - life (stress cycles)	Equivalent Stress GPa	(lb/in^2)
40	2.076×10^6	6.30	(913,827)
25	3.001×10^6	5.32	(771,938)
8	5.849×10^6	3.92	(568.690)
3	12.021×10^6	2.82	(408,900)
1	12.430×10^6	2.78	(402,684)
magnetic	12.480×10^6	2.77	(401.944)

Table 3

APPENDIX I

Bearing Material Properties and Test Parameters

Material: High carbon chromium EN31 steel (AISI 52100)
Compressive strength: 1.38GPa (0.2×10^6 lb/in^2)
Elastic Modulus: 207GPA (30×10^6 lb/in^2)
Poisson's Ratio: 0.3
Hardness: 750 VHN (MIN.)
Surface Roughness: 0.3 μm (12μ in) Inner/outer race
Surface Roughness: 0.05 μm (2μ in) Rollers
Reduced Elastic Modulus: 357GPa (51.8×10^6 lb/in^2)
Specific Conductivity: 50.4 W/mk
Coefficient of Linear Expansion: 15×10^{-6}/K
Bore Diameter: 25 mm (0.9843 in)
Test Speed: 5000 revs/min
Lubricant: Modified Mobil Jet II
Operating Temperature: 70°C (158°F) and 30°C (86°F)
Axial load: 0
Radial Load: 2957N (665lbf)
Min. Lubricant Film Thickness: 0.5767 μm (22.70μ in)
Max. Hertz's Contact Stress: 2.82GPa (408,900 p.s.i.)
Contact Size: 0.293 mm x 3.708 mm (0.01152 in x 0.146 in)
Max. Depth to Max. Shear Stress: 0.095 mm (0.00374 in)

APPENDIX II

Chemical Composition of EN39B steel.
Type: 4% Nickel Chromium Molybdenum

Gear Material by Percent Weight

Element	C	Mn	Si	Ni	Cr	Mo		
Weight %	0.12	0.25	0.10	3.90	1.00	0.15	p = 0.040)	Max.
	0.18	0.50	0.35	4.30	1.40	0.30	s = 0.050)	

APPENDIX III

Heat Treatment Process for EN39B Steel

Step	Process	Temperature K (^{o}F)	Time (hrs)
1	Carburize	1172 (1650)	8
2	Air Cool to Room Temperature		
3	Copper-plate All Over		
4	Reheat	922 (1200)	2.5
5	Air Cool to Room Temperature		
6	Austenize	1117 (1550)	2.5
7	Oil Quench		
8	Sub-zero Cool	189 (-120)	3.5
9	Double Temperature	450 (350)	2 each
10	Finish Grind		
11	Stress Relieve	450 (350)	2

N.B. All test gears were case-hardened and carburized as per above process to a nominal depth of 0.762 nm (0.030 inches)

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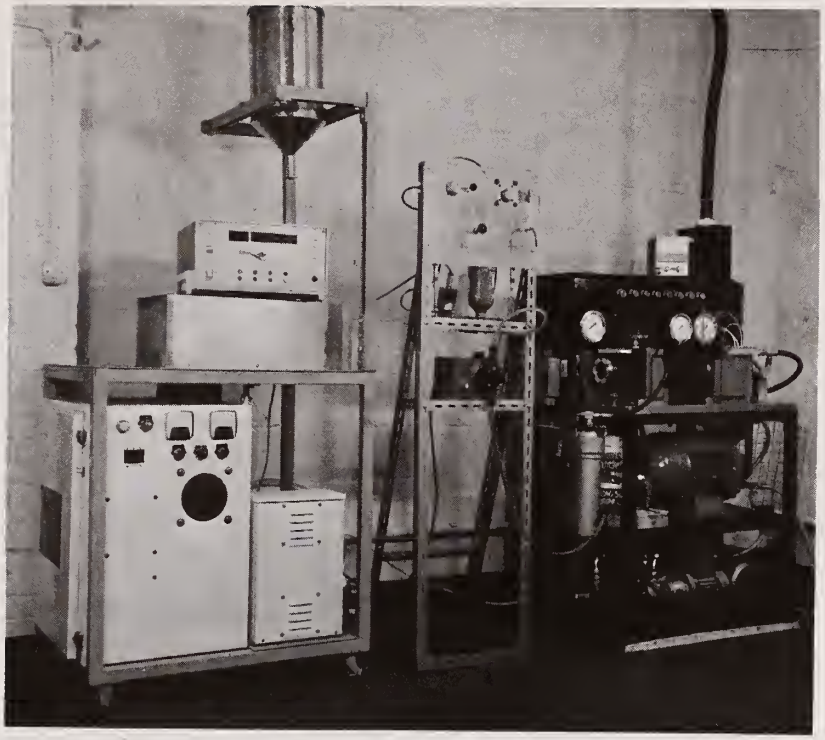


FIG. 1 Layout of Equipment.

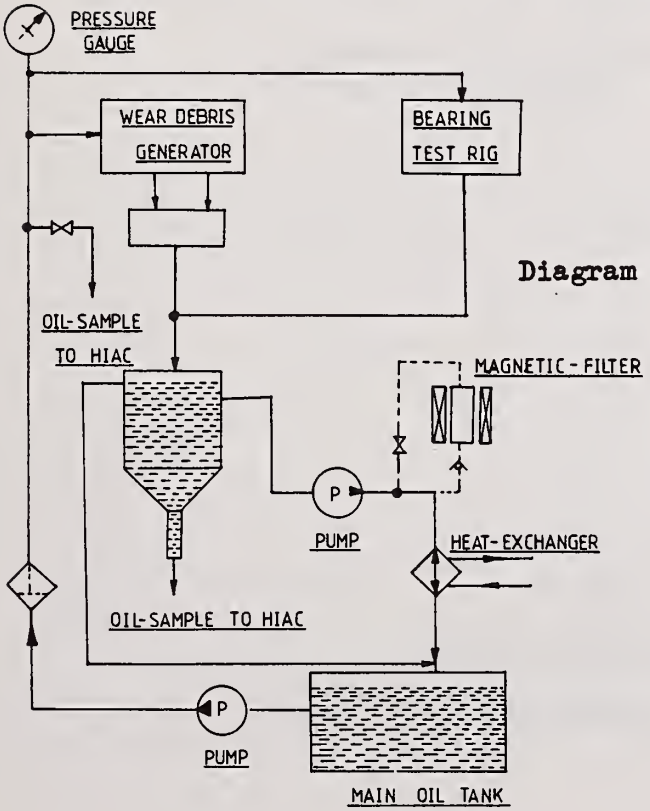


FIG. 2
Diagram of Test Oil Circuit.

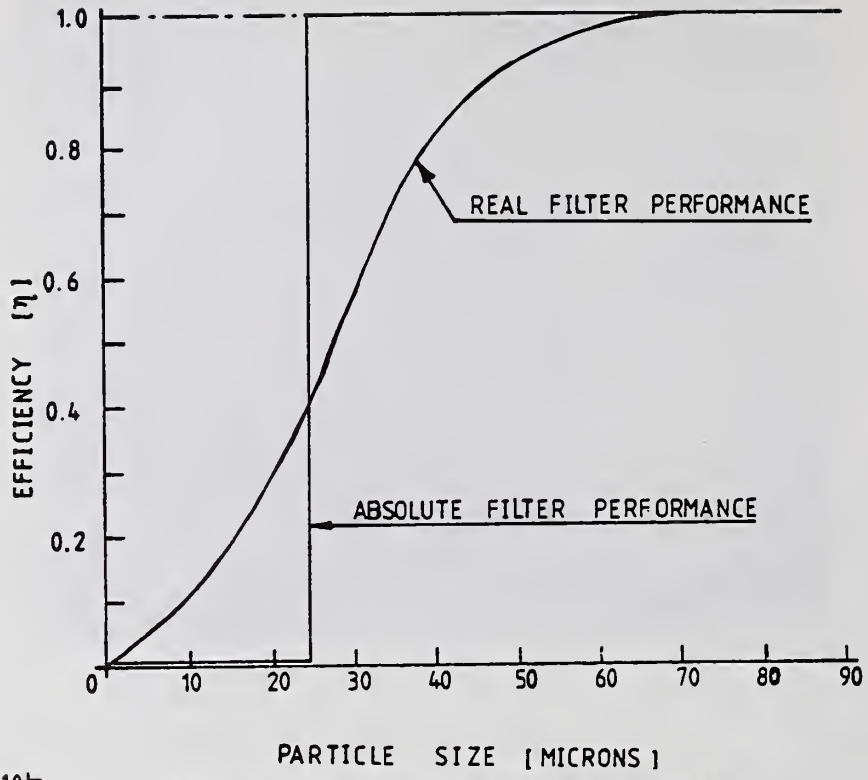


FIG. 3 Filtration Efficiency Curve.

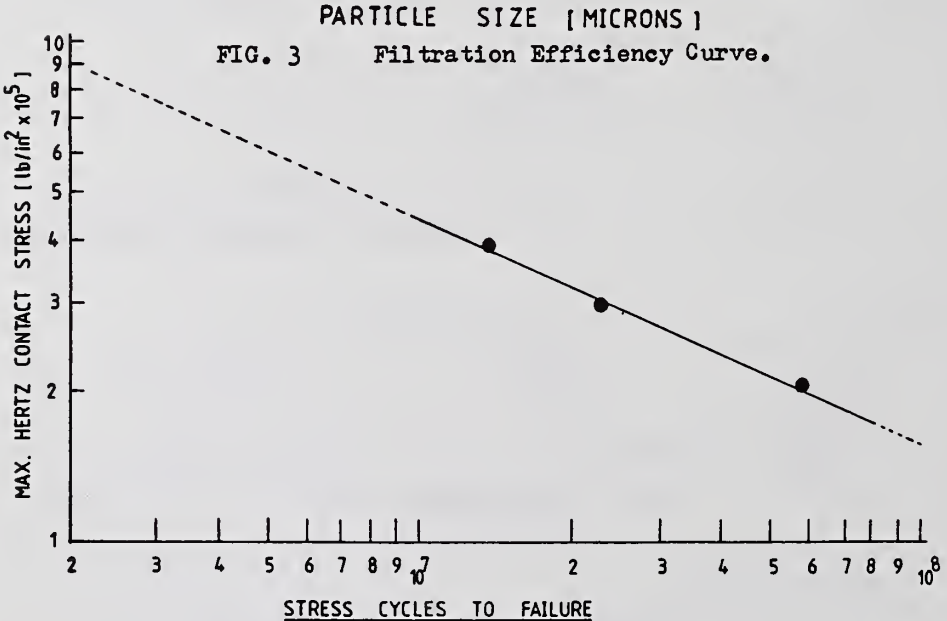


FIG. 4 Preliminary S – N Curve.

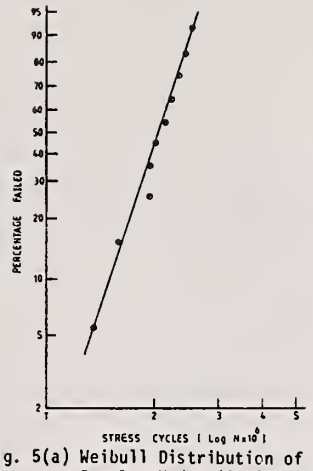


Fig. 5(a) Weibull Distribution of Fatigue Results Under 40 micron Filtration.

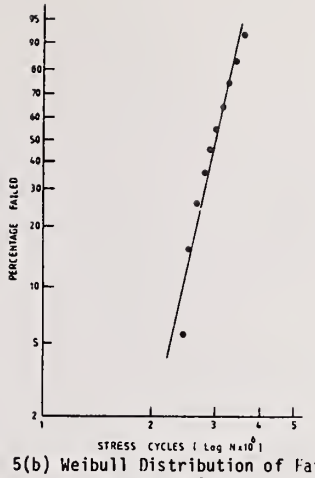


Fig. 5(b) Weibull Distribution of Fatigue Results Under 25 micron Filtration.

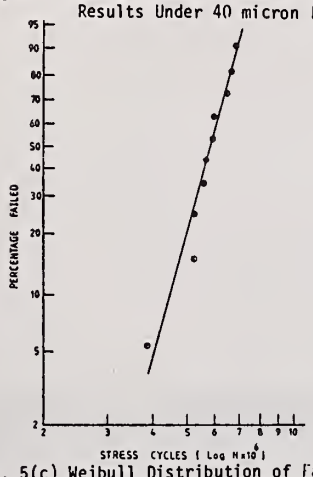


Fig. 5(c) Weibull Distribution of Fatigue Results Under 8 micron Filtration.

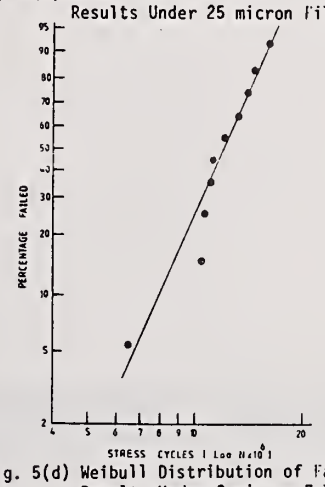


Fig. 5(d) Weibull Distribution of Fatigue Results Under 3 micron Filtration.

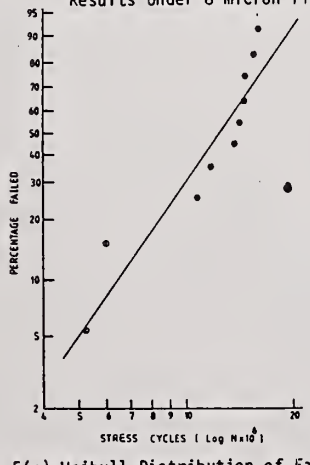


Fig. 5(e) Weibull Distribution of Fatigue Results Under 1 micron Filtration.

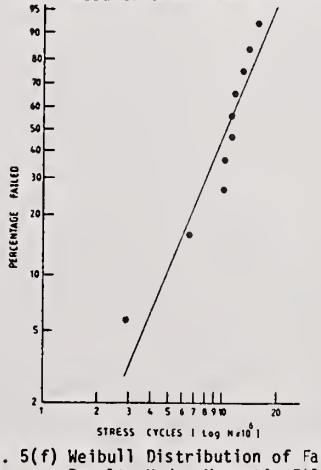


Fig. 5(f) Weibull Distribution of Fatigue Results Under Magnetic Filtration.

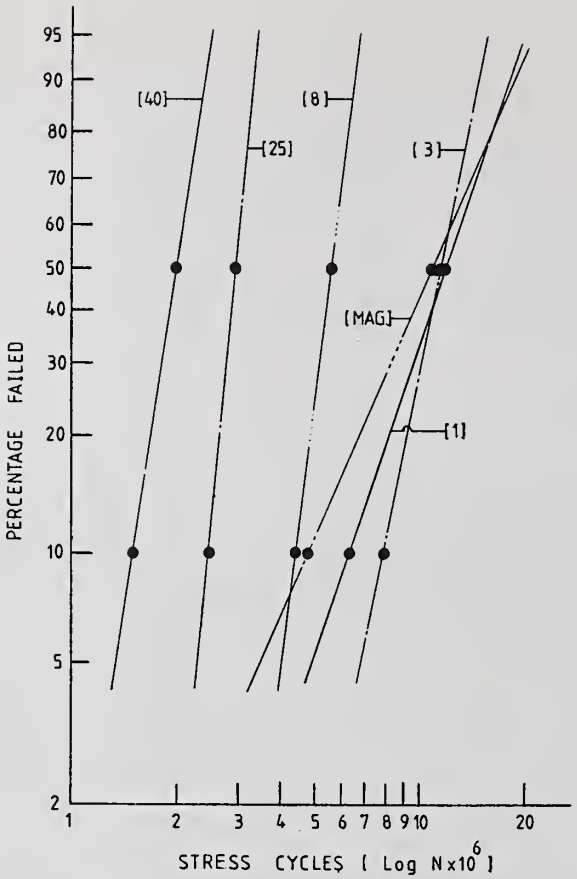


FIG. 6 Showing B10 and B50 Lives.

FIG. 7 Crack Propagation from an Indentation with 40 Micron Filtration (×500).

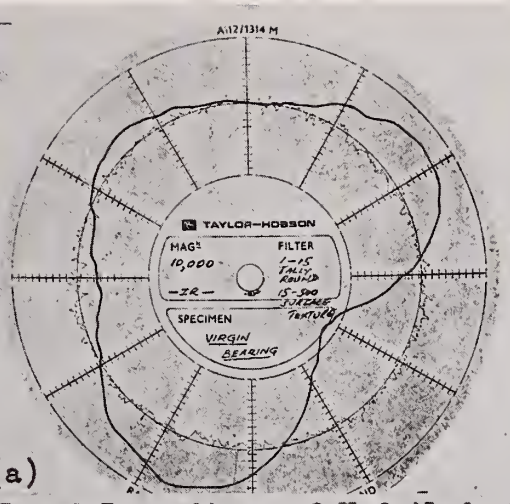


FIG. 8(a)
Taly - Round Recordings of Unfailed Bearing Races.

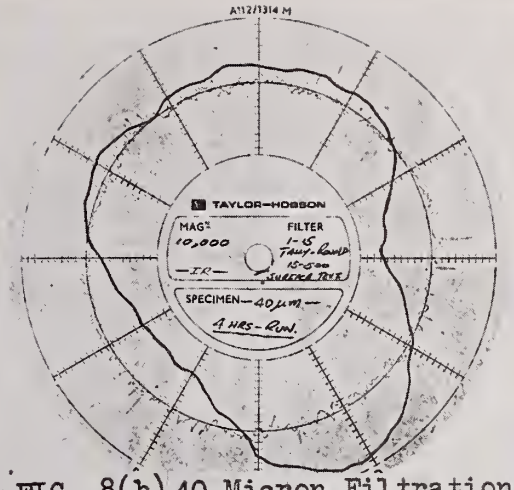


FIG. 8(b) 40 Micron Filtration.

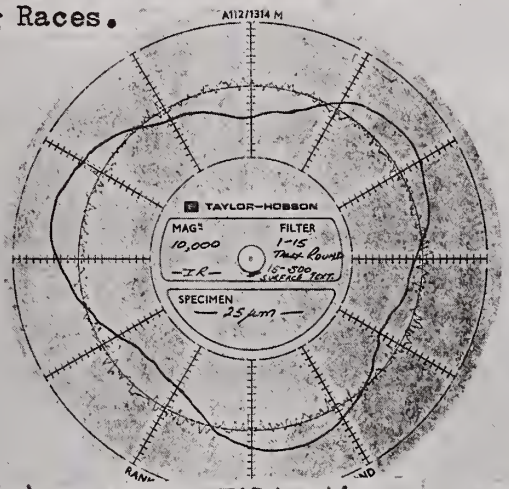


FIG. 8(c) 25 Micron Filtration.

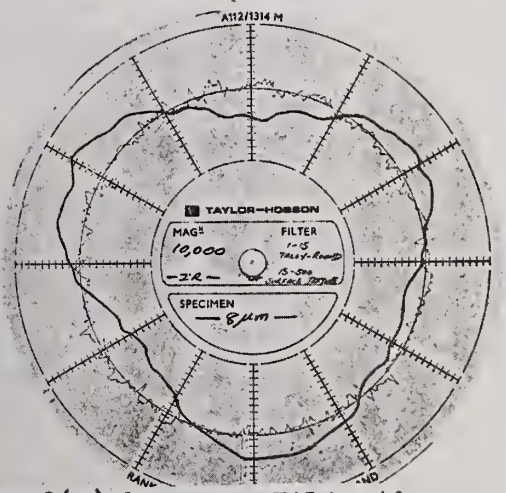


FIG. 8(d) 8 Micron Filtration.

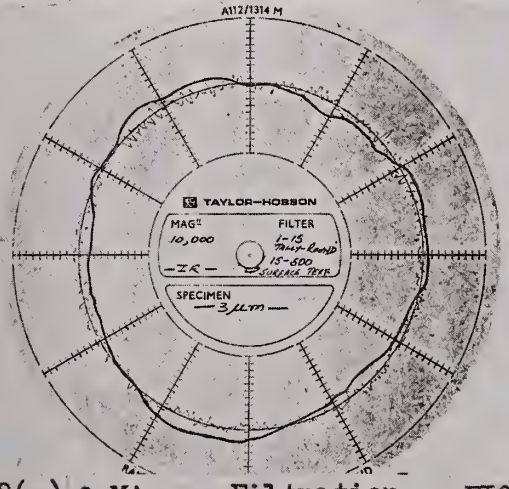


FIG. 8(e) 3 Micron Filtration.

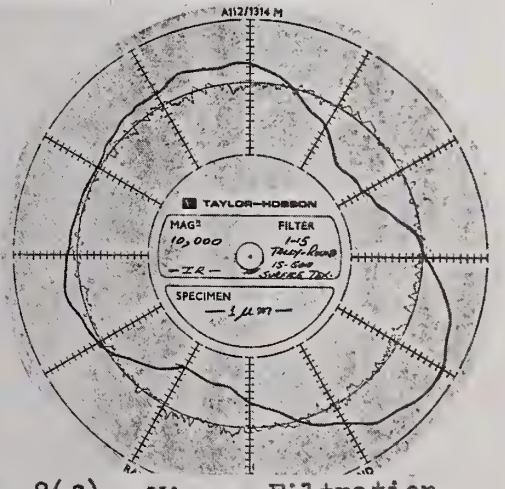


FIG. 8(f) 1 Micron Filtration.

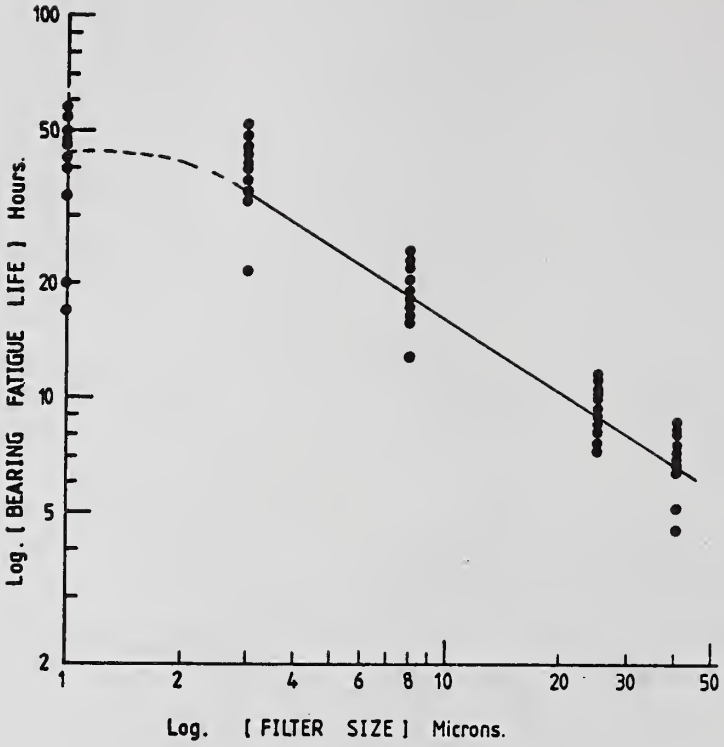


FIG. 9 B50 Life Curve.

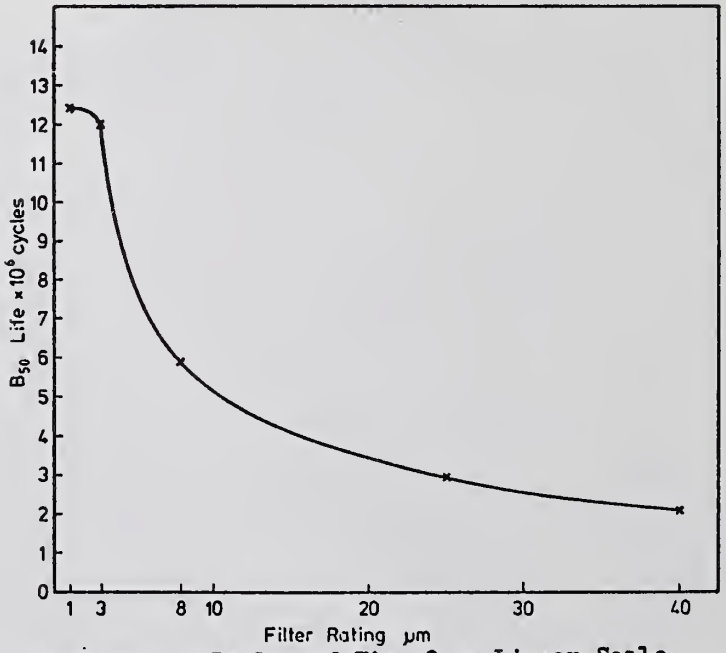


FIG. 10 Replot of Fig. 9 on Linear Scale.

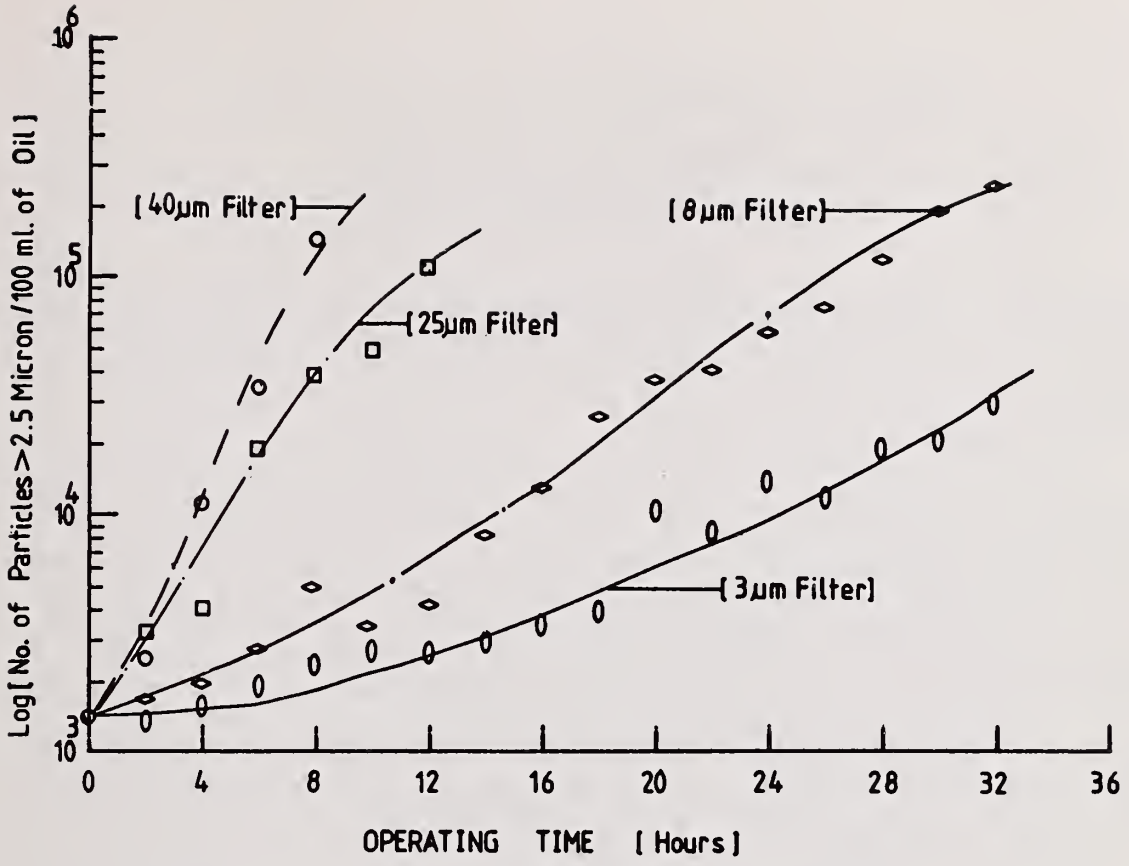
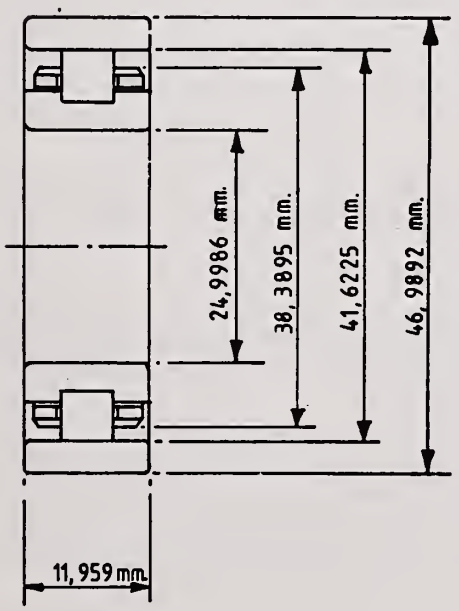


FIG. 11 Rate of Particle Generation.



CYLINDRICAL ROLLER BEARING

RHP - N1005

No. of Rollers	=	14
Roller Length	=	5.563mm (0.219 in)
Roller Diameter	=	5.563mm (0.219 in)
Diametral Clearance	=	0.031mm (0.0012 in)
Pitch Diameter	=	36.043mm (1.419 in)

FIG. 12 Test Bearing.

IMPROVED INSTRUMENT BEARING LUBRICATION

N. Rebuck and L. Stallings
Naval Air Development Center
Warminster, Pennsylvania 18974

Abstract: This paper will present the results of laboratory tests on three viscosity grades of synthetic hydrocarbon oils for the purpose of providing proposed specification requirements to cover these oils for military instrument bearing applications.

Synthetic hydrocarbon oils (fabricated from L Olifins) have become increasingly more popular in the last dacade. The initial widespread use of one such type fluid was as a base oil in a grease covered by Military Specification MIL-G-81322 which was originally developed for use in aircraft wheel bearings. This was followed by the use of a lower viscosity grade oil as an aircraft hydraulic fluid covered by Military Specification MIL-H-83282. Today both the grease and the hydraulic fluid are high volume items in the Navy Supply System. The grease is currently being used in a wide variety of military weapons systems applications including instrument bearings.

Interest in these fluids has also expanded to the industrial and commercial markets. Formulated fluids are available as multi-purpose gear lubricants, automotive engine oils, gas turbine lubricants, and high temperature bearing lubricants. Some of the major attributes of the oils include: (1) their high viscosity index, (2) their good thermal stability, (3) receptiveness of common additives and inhibitors, (4) their low temperature fluidity and (5) their compatibility with other lubricants and materials. Still another attractive feature is the outlook for their long term availability, an aspect which is of considerable interest to the instrument bearing community.

Key words: Aircraft hydraulic fluid; aircraft wheel bearing grease; instrument bearing lubrication; low temperature fluidity; synthetic hydrocarbon oils.

BACKGROUND

Instrument and instrument bearing lubrication is a demanding and specialized field in terms of requirements. Unfortunately, it has a very low lubricant market volume, thus making it difficult for the lubricant supplier to justify giving it a great deal of attention. As a result most of the lubricants used in the past for instrument bearing applications were designed for other uses, which often did not require the same quality control or the special properties that are often required in these applications.

Also, modifications or further developments of these lubricants were made without much if any concern for the requirement of the small volume applications.

An example of such a situation existed back in the 1960s at which time a mineral oil, designated Teresso V 78, was being used for lubricating spin axis gyro bearings. The V 78 oil was designed primarily for power generating equipment used in the electrical industry. When the manufacturer modified the process for making this oil, the military decided to develop a replacement oil designed specifically for use in spin axis bearings. This Air Force sponsored development program resulted in a product designated KG 80. A Military Specification MIL-L-83176 was written to cover this product. Actually, a series of different viscosity oils was produced under this program. With well defined processing steps using generally available mineral oil stocks, a primary objective of the Air Force program was to provide for a multi-sources capability of the finished product. However, obviously due to the low volume requirements, the original producer of the KG 80 lubricants, Kendall Refining Co., remains today as the only qualified supplier of this oil.

In the mid 1970s, Kendall indicated the possibility that they might discontinue the manufacture of the KG 80 oils, due to the small volume of the oils being requested. Although the producer was persuaded to continue supplying this oil, the military and industry became alarmed at the prospects of its discontinuance and began looking for potential replacements.

Since the synthetic hydrocarbon oils have many properties which are similar to those of the best petroleum oils it appeared that they were a logical choice for consideration in this area of application. Also, these oils were becoming more readily available in a variety of viscosity

grades and at competitive prices. More suppliers were introducing them into their product lines.

Several years ago the MPB Corporation made available three viscosity grades (high, low and medium) of the synthetic hydrocarbon fluids formulated specially for instrument bearing applications. These oils were formulated with the same antiwear additive, i.e. tricresyl phosphate, as is contained in the KG 80 oils. Although the specific oxidation inhibitor for these oils is not specified, it appears to be similar to or the same hindered bis-phenol that is required in the KG 80 oil by the MIL-L-83176 Specification.

At the request of the Naval Air Systems Command, laboratory evaluations were initiated on these oils at the Naval Air Development Center, with the objective of comparing their properties to those of the KG 80 oils and establishing proposed specification requirements.

TESTS AND RESULTS

In order to develop data, not only suitable for comparison with KG 80 but also showing the differences among the MPB Oils themselves, all the laboratory chemical and physical tests for each of the oils were conducted under the same conditions. The results of the tests on the highest viscosity grade (similar to KG 80) MPB Oil, designated MC 119, are compared with those on the KG 80 oil and against requirements of Specification MIL-L-83176. The results of the low and medium viscosity grade oils designated MO 18 and MC 75 respectively are compared with those of a synthetic ester instrument oil MB 20B and against requirements of MIL-L-81846 Specification to which the MB 20B oil is qualified.

PHYSICAL PROPERTIES

Standard viscosity determinations were made on each of the oils at the normal 210° and 100°F temperatures. Additional viscosity tests were conducted on the MC 18, MO 75 and MB 20B oils at -40° and -65°F. The viscosity index for each oil was calculated. These results are shown in Tables I and II.

Pour points and Flash points were also determined on each of the oils using standard ASTM procedures with results shown in Tables I and II as well.

A superior viscosity-temperature relationship and pour point is noted for the MO 119 over that of the KG 80, while the KG 80 has an advantage with its higher flash point.

The MO 18 and MB 20B oils have very similar viscosities. The MO 18 has a slight advantage at -65°F even though the MB 20B has a considerable edge in the calculated viscosity index. MB 20B also has a slightly higher flash point. The MO 75 has the advantage at the higher temperature while having a somewhat disadvantage at the lower temperatures.

OXIDATION-CORROSION

Oxidation-corrosion tests were conducted on each of the oils with the exception of the MB 20B. Results are shown in Tables III and IV. A modified Method 5308 of Federal Test Method Standard 791 was used to test the oils. The metals used were those called out by MIL-L-81846 except for the aluminum which was used in place of a mild carbon steel. The test time and temperature were also those required by MIL-L-81846 which is significantly greater than that called out by the MIL-L-83176 specification.

There is a significant difference between the MO 119 and the KG 80 oil in the % of change in viscosity with the KG 80 showing considerable increase in viscosity. A similar situation exists with acid number indicating a great advantage in oxidation resistance for the MO 119.

Although no tests were conducted on the MB 20P it has obvious advantages over the MO 19 and MO 75 based on the MIL-L-81846 requirements.

THIN FILM STABILITY AND VOLATILITY

Typical instrument bearing applications require extremely minute quantities of lubricant so that high bearing surface area to lubricant volume ratios exist for the entire life or maintenance cycle of the bearing. Thin film properties can be quite different from those of the bulk properties of a lubricant.

In the thin film stability test required by MIL-L-81846, a 0.35 gram sample of the test oil is placed in a stainless steel planchet (5 cm. diameter and 1 cm. deep). The planchets containing the lubricants are then held in a thermostated, gravity convection oven maintained at 350 ± 4°F for 6½ hours. The weight loss and final appearance of the oil is noted.

The results of the thin film stability and bulk evaporation tests are shown in Tables V and VI.

It appears that XG 80 has an advantage over MC 119 for the volatility portion of this test although MC 119 has a slight edge in flow.

Again the MR 20F shows excellent resistance to change as indicated by its free flowing ability even after having lost 76% of its weight due to evaporation. It should be noted that the temperature control was not held to the requirements of MIL-L-81846, although relative comparisons of the results are valid since the tests were all conducted at the same time.

FOUR-BALL WEAR

Four ball wear tests are most frequently conducted using standard 52100 steel ball specimens. It should be noted, however, that the majority of instrument bearings today are fabricated from 440C stainless steel. Also, stainless steel is much more difficult to lubricate under boundary conditions than is the 52100 steel. Four-ball wear tests were therefore conducted using both 52100 and 440C specimens. Test conditions and results of tests are shown in Tables VII and VIII.

These results indicate slightly better boundary lubrication for 52100 steel with the XG 80 while the opposite is true for 440C stainless steel.

A somewhat different effect is shown with the ester lubricant. The synthetic hydrocarbon oils show definite advantages under all conditions except under the high load for the 440C specimens.

R-4 Bearing - Lubricant Life

Bearing-lubricant operating life tests were conducted on all but the MC 75 sample. The tests were run in accordance with ASTM Method D3237 except that bearings having porous phenolic retainers were used in place of the ribbon type retainers. The bearings were lubricated by the manufacturer using the vacuum impregnation technique. Test conditions and results are shown in Tables IX and X.

The failure criteria for these bearing tests is a torque increase of 5 times the running torque taken one hour after reaching test temperature. The test temperature is normally stabilized after one hour of running.

The results of the bearing tests shown here do not indicate bearing lubrication superiority, of one type of lubricant over another, in all or even the majority of instrument bearing applications.

They do however show the need for further investigation and testing in the instrument bearing applications field.

CONCLUSION

The synthetic hydrocarbon oils as represented by those tested in this program were shown to have excellent properties when compared with both the MC 80 super-refined petroleum oil and the highly effective MB 20B ester instrument oil. Another advantage for these oils is the outlook for their apparent long term availability based on the increased demand from industrial and commercial markets.

Physical Property Comparison

of

MPB MO 119 and Kendall KG 80

Test	Method	Results MO 119	Results KG 80	MIL-L-83176 Requirement
Viscosity, CS @210°F	D445	14.41	14.96	14.76 - 15.78
@100°F	D445	120.9	165.1	Report
Viscosity Index	D2270	131	98	100 Min.
Pour Point, °F	D97	-45	-5	25 Max.
Flash Point, °F	D92	510	550	500 Min.

TABLE I

Physical Property Comparison

of

MPB MO 18, MO 75 and Grignard MB 20B

Test	Method	Results MO 18	MO 75	MB 20B	MIL-L-81846 Requirement
Viscosity, Cs @210°F	D445	3.68	9.94	3.58	3.45 Min.
@100°F	D445	17.53	66.32	14.2	14.0 Min.
-40°F	D445	2459	27504	1886	-
-65°F	D445	9987	-	12124	13000 Max.
Viscosity Index	D2270	119	146	158	-
Pour Point, °F	D97	-85	-65	-80	-70°F Max.
Flash Point, °F	D92	455	495	470	410 Min.

TABLE II

Corrosion - Oxidation Comparison

of

MPB MO 119 and Kendall KG 80

Test	Method	Results		MIL-L-83176 Requirement
		MO 119	KG 80	
Acid No.	D974	0.03	0.03	-
Corrosion - Oxidation *	FTM			*
72 Hrs. @350°F	5308			48 Hrs. @300°F
(a) % Change in Vis. @100°F		+0.6	+61.0	-5 to + 20
(b) Change in Acid No.		+1.76	+4.70	2.0 Max.
(c) Appearance After Test		Small amt. of light colored insolubles	Small amt. of dark colored insolubles	-
(d) Change in Wt. (mg/cm^2)				
(1) 410 Steel		0.01	0.01	-
(2) 52100 Steel		0.00	0.01	-
(3) Silver		0.01	0.00	-
(4) Copper		0.04	0.16	0.6 Max.
(5) Aluminum		0.02	0.00	-

* 5 liters of air/hr is passed through sample

TABLE III

Corrosion - Oxidation Comparison

of

MPB MO 18, and MO 75

Test	Method	Results MO 18	Results MO 75	MIL-L-81846 Requirement
Acid No.	D974	0.03	0.03	-
Corosion - Oxidation *	FTM			**
72 Hrs. @350°F	5308			72 Hrs. @350°F
(a) % Change in Vis. @ 100°F		+24.0	+27.0	-5 to +15
(b) Change in Acid No.		+4.16	+ 3.05	1.5 Max.
(c) Appearance After Test		Small amt. of light colored insolubles	IBID	No sludge or insolubles
(d) Change in Wt. (mg/cm^2)				
(1) 410 Steel		0.00	0.01	0.2 Max.
(2) 52100 Steel		0.01	0.01	0.2 "
(3) Silver		0.01	0.02	0.2 "
(4) Copper		0.05	0.08	0.6 "
(5) Aluminum		0.03	0.01	-

* 5 liters of air/hr is passed through sample
** 3 liters of air/hr is passed through sample

TABLE IV

Thin Film Stability and Volitility Comparison

of

MPB MO 119 and Kendall KG 80

Test	Method	Results MO 119	Results KG 80	MIL-L-81376 Requirement
Thin-film Stability (6 1/2 Hrs @350°F)	MIL-L-81846			
(a) Evaporation, %		47.0	31.0	-
(b) Tackiness		very slight	very slight	-
(c) Lacquer/sludge		very little lacquer	very little lacquer	-
(d) Flow		slightly restricted	moderately restricted	-
Evaporation, % 22 Hrs @350°F	D972	5.34	2.32	

TABLE V

Thin Film Stability and Volitility Comparison

of

MPB MO 18, MO 75 and Grignard MB 20B

Test	Method	Results MO 18	MO 75	MB 20B	MIL-L-81846 Requirement
Thin-Film Stability (6 1/2 Hrs @350°F±10°	MIL-L-81846				6 1/2 Hrs @350°F±4°
(a) Evaporation, %		79	53	76	75 Max.
(b) Tackiness		slight	slight	very slight	None
(c) Lacquer/Sludge		slight amt of lacquer	IBID	very slight amt of lacquer	None
(d) Flow		slightly restricted	slightly restricted	free flowing	free flowing
Evaporation, % 22 Hrs @350°F	D972	26.33	5.99	12.22	22.0 Max

TABLE VI

Four-Ball Wear Data Comparison

of

MPB MO 119 and Kendall KG 80

Test		Method	Results		MIL-L-83176 Requirement
			MO 119	KG 80	
Four-Ball Wear 1 Hr @ 167°F-1200 RPM					1 Hr @ 167°F
	Load (Kg)				600 RPM
52100	40		0.62	0.52	0.65 Max
"	20		0.39	0.36	-
"	10		0.22	0.22	0.30 Max
1 Hr @167°F-600 RPM					
	Load (KG)				
440C	40		1.44	1.86	-
"	20		0.44	0.58	-

TABLE VII

Four-Ball Wear Data Comparison

of

MPB, MO 18, MO 75 and Grignard MB 20B

Test	Method	Results MO 18	MO 75	MB 20B	MIL-L-81846 Requirement
Four-Ball Wear					
1 Hr @167°F-1200 RPM					
	Load (KG)				
52100	40	0.74	0.68	1.13	-
"	20	0.46	0.41	1.01	-
"	10	0.27	0.22	0.78	-
1 Hr @ 167°F-600 RPM					
	Load (KG)				
440C	40	2.67	1.43	1.08	-
"	20	0.48	0.46	0.72	-

TABLE VIII

Sunoco R-4 Bearing Lubricant Life Comparison

of

MPB MO 119 and Kendall KG 80

Test Conditions	Results (Hrs) MO 119	KG 80
Speed - 12000 RPM		
Load - 1/2 lb. Radial	40.4	18.0
- 5 lb. Axial	100.0	20.0
Temp - 300°F	86.0	20.0
Bearing: MPB	100.0	20.0
SR4MCHH7	74.8	9.6
Retainer - Phenolic* Avg	80.2	17.5

Test Cycle: 20 Hrs Running

4 Hrs Shutdown

* Vacuum Impregnated by MPB

TABLE IX

Sunoco R-4 Bearing - Lubricant Life Comparison

of

MPB M018 and Grignard MB 20B

		Results (Hrs)	
Test Conditions		MO 18	MB 20B
Speed - 12000 RPM			
Load - 1/2 lb Radial		140.0	9.6
5 lb Axial		57.5	12.0
Temp - 250°F		150.5	16.2
Bearing: MPB		60.0	6.5
SR4MCHH7		190.2	13.3
Retainer - Phenolic*	Avg	119.6	11.5

Test Cycle: 20 Hrs Running

4 Hrs Shutdown

* Vacuum Impregnated by MPB

TABLE X

ADVANCED STRUCTURES MAINTENANCE TECHNOLOGY

Nikolaos (Nick) Caravasos
Advanced Composites Technology
Boeing Vertol Company
Philadelphia, Pennsylvania 19142

Abstract: The use of composites in aircraft structures has been increasingly evident in the last decade as the drive for lower cost, lighter weight, more reliable aircraft structure has intensified. Composite structural systems are meeting these challenges and their use is being accepted and is expected to expand in the future. New hybrid constructions where materials such as graphite are integrally fabricated with fiberglass or Kevlar designs to control stiffness and provide fail safety while maintaining high strength to weight ratio will require unique repair and quality control methods.

This paper (a) summarizes the state-of-the-art in structural repair and maintenance of advanced composite structures, (b) identifies technological gaps, and (c) outlines a development and test program to fill in these technological gaps.

Key words: Composite materials; Maintenance; Repairability; Sandwich structure; Laminate structure, Testing

List of Abbreviations

FRB - Fiberglass Rotor Blade
Gl/Ep - Fiberglass/Epoxy
Gr/Ep - Graphite/Epoxy
Gr/Kev/Ep - Graphite-Kevlar/Epoxy
HFT - Honeycomb Fiber Truss
Kev/Ep - Kevlar/Epoxy
RT - Room Temperature
Ti - Titanium
RH - Relative Humidity

Introduction: Boeing Vertol Company engineers and manufacturing personnel have been engaged in advancing the state-of-the-art in composite structures applications since the first helicopter fiberglass fuselage section was fabricated in 1956. Repair of composite structures has been a primary consideration on fiberglass rotor blades for the CH-46 and CH-47 helicopters, Figures 1 and 2. It included step-by-step repair procedures, validation of repairs through testing and inspection as well as formulating training programs for field repair.

Composite structures will constantly be subjected to the same 'real world' heavy handed use, enemy threat levels and inexperienced personnel as the systems they will replace. As such, they will become damaged in a multitude of ways ranging from ballistic impact damage, to abuse by operating personnel, to environmental effects.

Repair of composite structures is, therefore, of primary importance, as it has been on the CH-46 and CH-47 fiberglass rotor blades. Although repairs of airframe structures will generally be less critical than rotor blades, rapid repairs in a field or "on aircraft" environment along with simplification of repair procedures and equipment must be emphasized.

A number of repair problems have been solved in the current uses of composites; however, numerous problems are still unresolved. As new hybrid materials are used more and more in structural applications, a great need arises not only in designing such structures to meet the design requirements, but also in maintaining them in the field. Field repair adaptability on the aircraft using aircraft power sources will provide greater aircraft utilization, and less maintenance man-hour expenditure and less facilities cost.

Repair techniques for composites, although different from standard metal repair methods, can be readily mastered by basic or intermediate skill level personnel. Training requirements are not extensive or complicated. Experience has shown that once maintenance personnel have learned the fundamentals of (1) proper preparation of the repair area, (2) cleanliness and (3) strict adherence to handling and mixing of adhesives, repair of composites is a relatively easy task for the average mechanic.

The typical resource requirements that are necessary for performing repairs are:

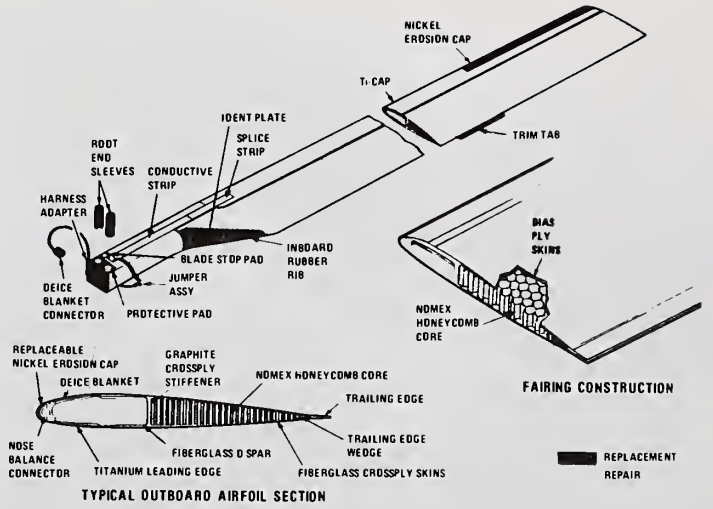


Figure 1. H-46 FRB Repair Program

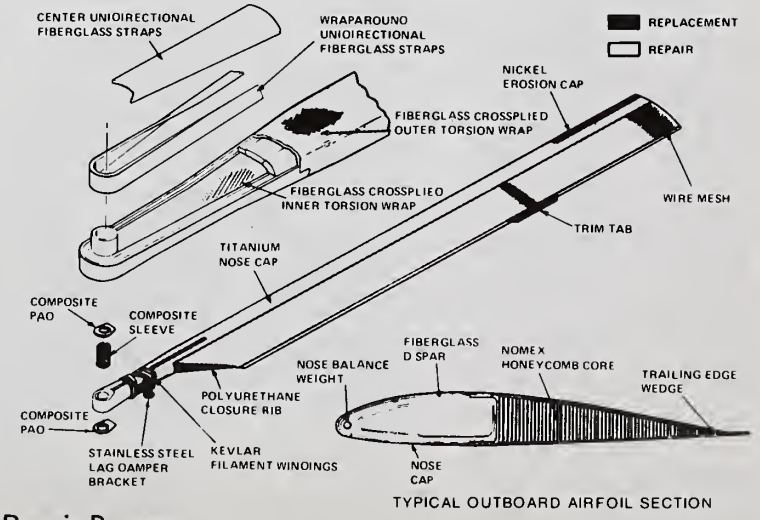


Figure 2. H-47 FRB Repair Program

- Materials
- Support equipment
- Repair procedures
- Personnel skills
- Inspection

Typical materials currently in use are as follows:

- Solvents, e.g., acetone or aliphatic naptha
- Adhesives, e.g., EC2216, EA9309.3, EA9628
- Resin, e.g., EPON 828/DTA
- Sealant, e.g., Proseal 890
- Fabrics, e.g., teflon/Dacron-S-1854, teflon/ fiberglass, fiberglass cloth #181 & #1500, peel ply, scrim cloth, cured crossply
- Fillers, e.g. urethane foam 2-lb/cu. ft. density, non-metallic honeycomb core, etc.
- Coatings, e.g., primer, antistatic coating, lacquer

Typical examples of repairs were developed for both the CH-46 and CH-47 fiberglass rotor blade repair programs and are schematically depicted on Figures 3 through 5. Step-by-step procedures provide the mechanic with didactic examples for performing repairs such as, full core, partial core, and skin repairs. Core repairs can also be performed using foam as a plug instead of the nomex honeycomb core as shown on Figure 6. Foam can effectively be substituted only in small core repairs because of the loss in structural integrity. Adaptability of such repair techniques was recently demonstrated on a Boeing 757 airplane (350°F cure) wing panel section fabricated from Kevlar skins with HFT honeycomb core. Several RT repairs were performed including a transitioned core and skin repair, a core replacement with 2-pound density foam and a skin replacement using fiberglass skin instead of Kevlar skin. These repairs are shown on Figures 7 and 8.

Inspection also plays an important part in maintaining composite structures. This is due to the fact that damage to the exterior surface of composites can cause localized internal failure which is not readily detectable unless a thorough inspection is made. Therefore, whenever cracks, dents, tears, punctures, etc., are discovered during routine scheduled inspections, a detailed follow-up inspection must be made in order to assess the damage and make proper repairs. In addition to visual inspection, other nondestructive test techniques may be required such as coin-tapping and ultrasonic testing with portable equipment.

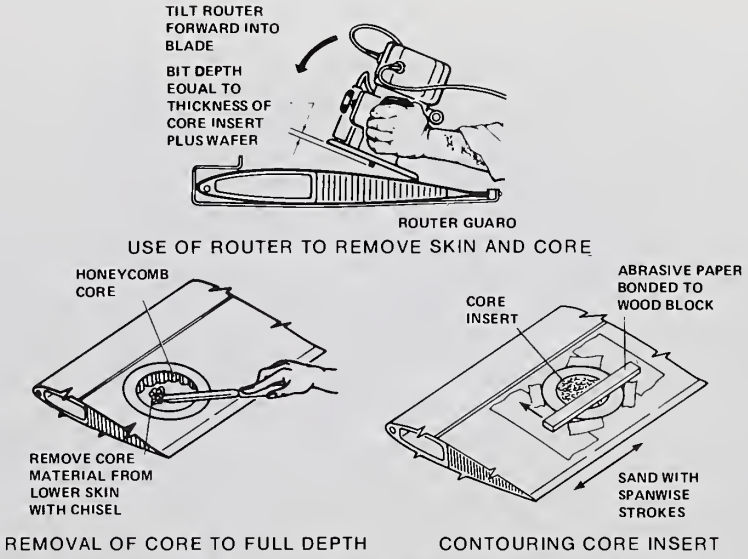


Figure 3. Typical Core Removal and Repair

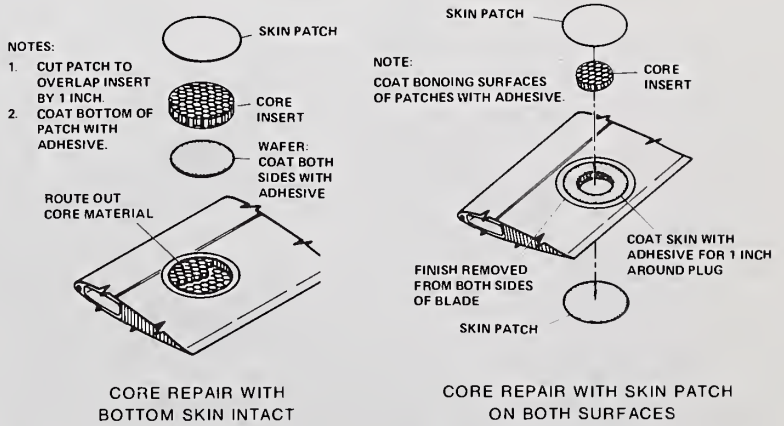


Figure 4. Typical Core Repairs

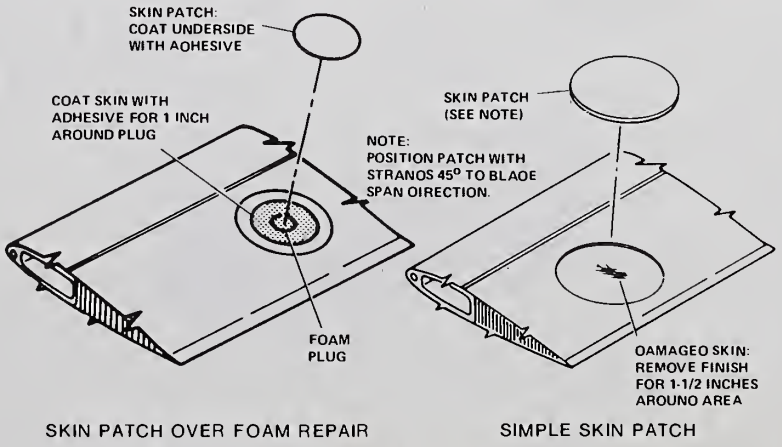


Figure 5. Skin Repairs

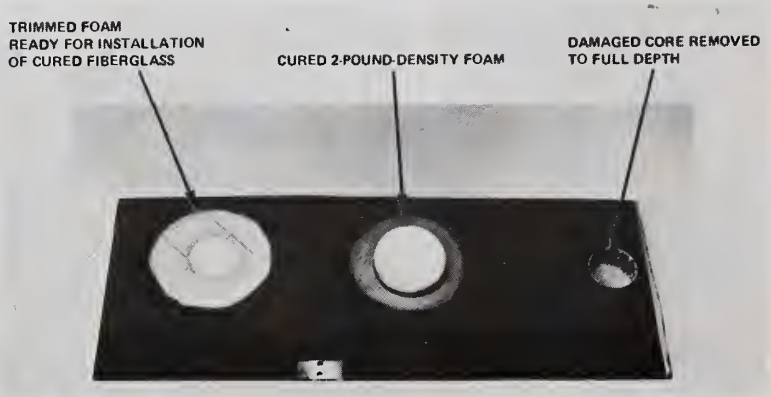


Figure 6. Foam Used to Replace Damaged Core

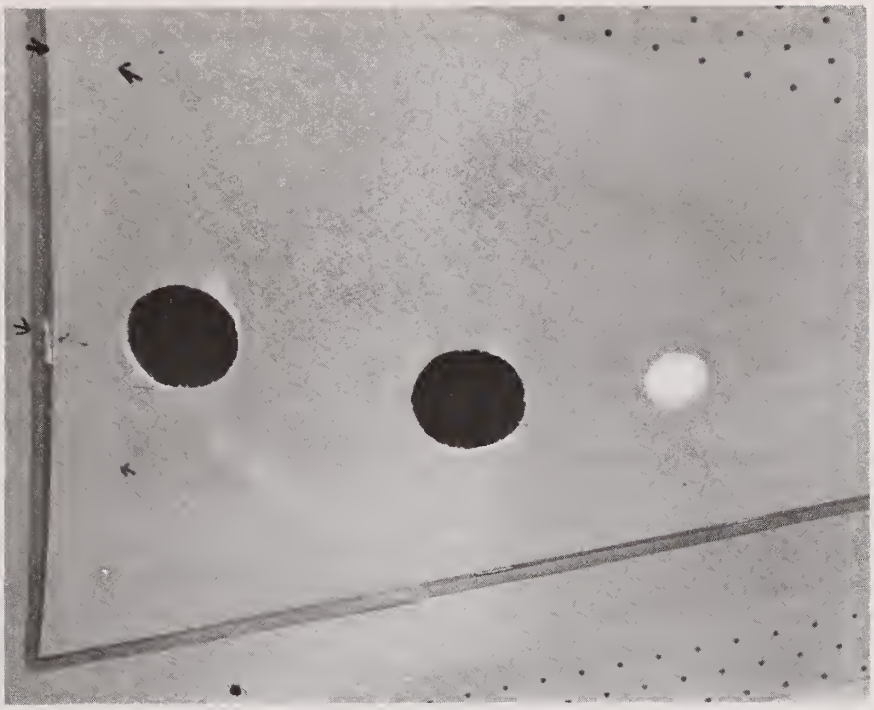


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Figure 7. 757 Wing Panel Repairs in Progress

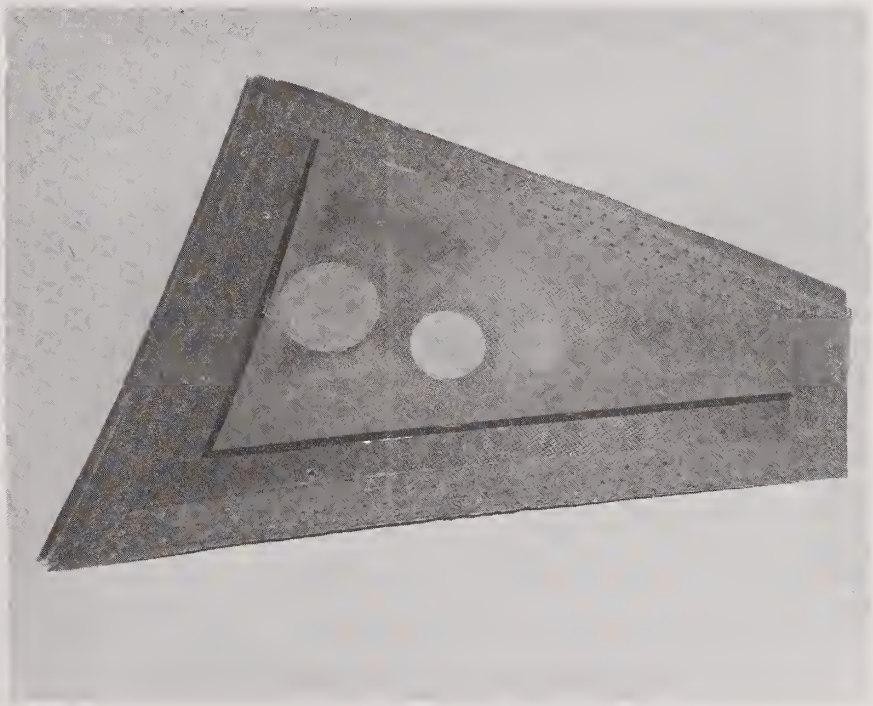

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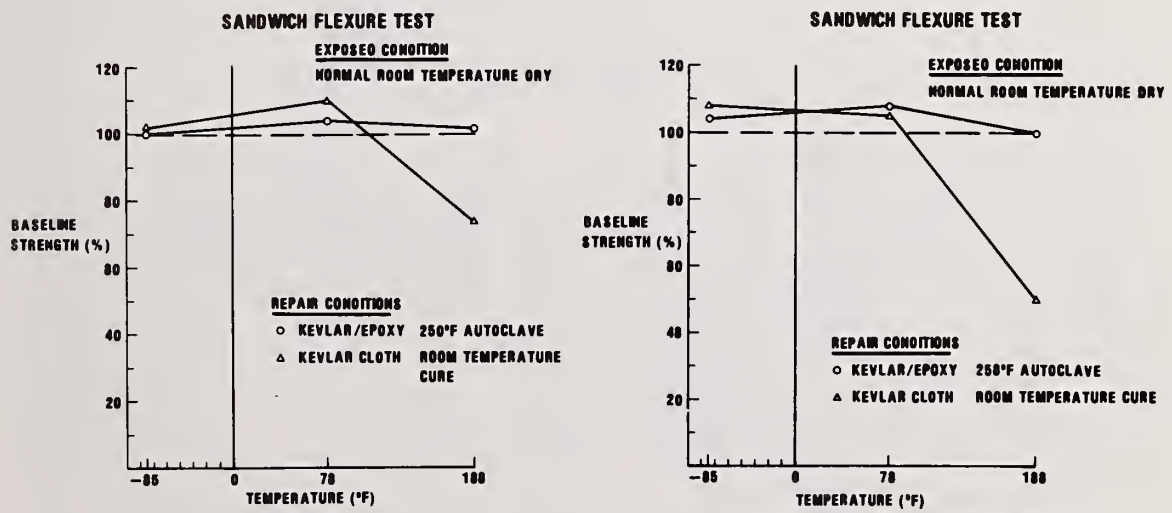
Figure 8. 757 Wing Panel Completed Repairs

Problematic Observation: Due to recent implementation of composites for structural applications, limited data are available regarding advanced composite structures to adequately define repair problems both in the laminate and sandwich form. From the information that is available several broad observations can be drawn. First, the major causes of failure in honeycomb sandwich designs were core-to-skin delamination caused by either faulty lay up, cleaning and cure techniques, or inadequate design with materials frequently affected by environmental conditions such as moisture and temperature. Second, the failure of composite laminates was also due to inadequate detail designs, materials, and environmental protection systems. In the case of honeycomb core, ingress of water into the core cells nearest to the panel edge, or in areas of panel cut outs and fasteners where capillary action and barometric pressure and altitude changes induce cell-to-cell moisture migration, leads eventually to skin/core delamination failures. Complete cell boundary encapsulation in the adhesive matrix is required to eliminate or minimize cell-to-cell moisture migration.

Repair techniques of advanced composite airframe structures have been studied more extensively by the commercial fixed-wing industry because of their relatively wider use of such structures. In the rotary wing area, repair of advanced composites has largely been limited to rotor blades and secondary structures. Advanced composite concepts, under contract or independent research and development, are now being applied to primary fuselage applications in helicopters. Most of the work up to now has been conceptual but firm designs are now being implemented. As advanced composites assume an increasingly more important role in structural applications, repair techniques of such structures will be developed and substantiated against the same operational criteria limits as their metallic counterparts. These limits encompass extreme climactic and environmental conditions, i.e., temperatures ranging from -65°F to 160°F, prolonged high relative humidity, and exposure to fluids such as oil, salt water, fuel, and maintenance solvents.

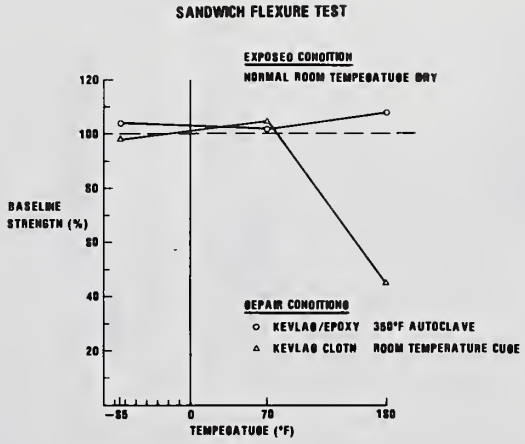
The repair concepts for advanced composite structures will have to satisfy the above limits as related to strength, stiffness, and functional performance. The limited work thus far completed points to several technological gaps. Materials such as graphite/epoxy, Kevlar/epoxy, Kevlar-graphite/epoxy used in sandwich panels and laminated plate specimens have been tested at various operational conditions. Skin patches were composed of similar thickness

materials with fiber orientation matching the skin fibers. Two layers of fabric were used to replace each layer of unidirectional tape. Representative results as shown on Figures 9 and 10 reveal that all room temperature curing systems tend to lose strength at temperature (i.e. > 180°F) which is why they haven't been used for loaded primary structure. The prepreg patch applied at 350°F in an autoclave retained its strength throughout the range of temperature testing. Conditioned RT repair specimens (conditioned usually for 30 days at 140°F/100% RH) performed equally as well at -65°F and at RT as the nonconditioned specimens while similarly experiencing loss of strength at 180°F. It appears from this set of data that the high temperature exposure of RT cured patches produces reduced strength and therefore, this consideration must be given to repairs of highly loaded structures. Additionally, the critical temperature for serviceability of RT cured patches is further reduced by exposure to a combination of hot and humid environmental conditions. The loss of strength characteristic at high temperatures does not prevent the effective use of RT repairs as evidenced by the excellent results demonstrated in the FRB program. However the repair criteria (depth, extent, etc.) must recognize the effect, especially for highly loaded structures.

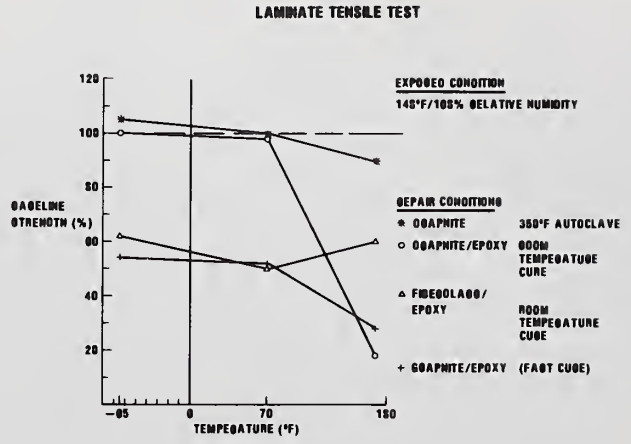


KEVLAR/Epoxy KEVLAR – Graphite/Epoxy

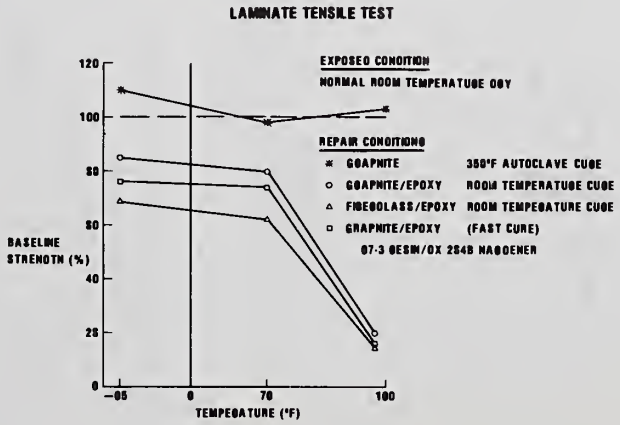
Figure 9. 250°F Cure Specimens



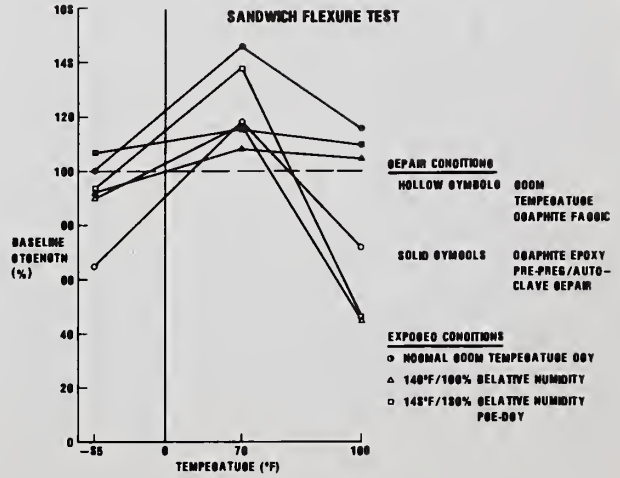
KEVLAR-Graphite/Epoxy



Graphite/Epoxy



Graphite/Epoxy



Graphite/Epoxy

Figure 10. 350°F Cure Specimens

Technological gaps: A summary of tests compiled from published data is shown in Table 1. One can see from this long list of available data that all tests were performed on either sandwich or laminate specimens which constitute aircraft skins. Very little or no work at all has been performed on frame sections or structural fitting applications. Additionally, other areas of interest where little or no work at all has been performed are:

A - Sandwich Panels
  1) Primary Structure Construction
     a) Use of HFT core
     b) Use of foam instead of core
     c) Use of adhesive bonding
  2) Repair components
     a) precure skin patches
     b) HFT core
     c) Nomex core
     d) Polyurethane foam
  3) Testing
     a) high temperature exposure/testing
     b) high humidity exposure

B - Laminates
  1) Primary Structure Construction
     a) Kev/Ep
     b) Gr/Kev/Ep
     c) adhesive bonding
  2) Repair Concepts
     a) Kev/Ep
     b) Gr/Ep
  3) Testing
     a) Prior exposure
     b) High/Low temperature tests

After thoroughly examining the data, a specimen matrix was constructed, Table 2 representing typical specimens of advanced composite materials for aircraft application. The asterisk(*) areas signify that sufficient test data are available to conclusively determine damage/repair limitations. The existing data, although thorough, are limited only to laminate and sandwich coupons. The difficulty arises in that no frame sections nor structural fittings have been tested. These are common structural aircraft applications which would require more complex repair techniques.

It is evident that further development is required to broaden and/or improve the repair limits of advanced composites, especially in high temperature/high humidity environments. Room temperature cure repairs when subjected to high temperatures produced strength results that were

Table 1. Test Summary

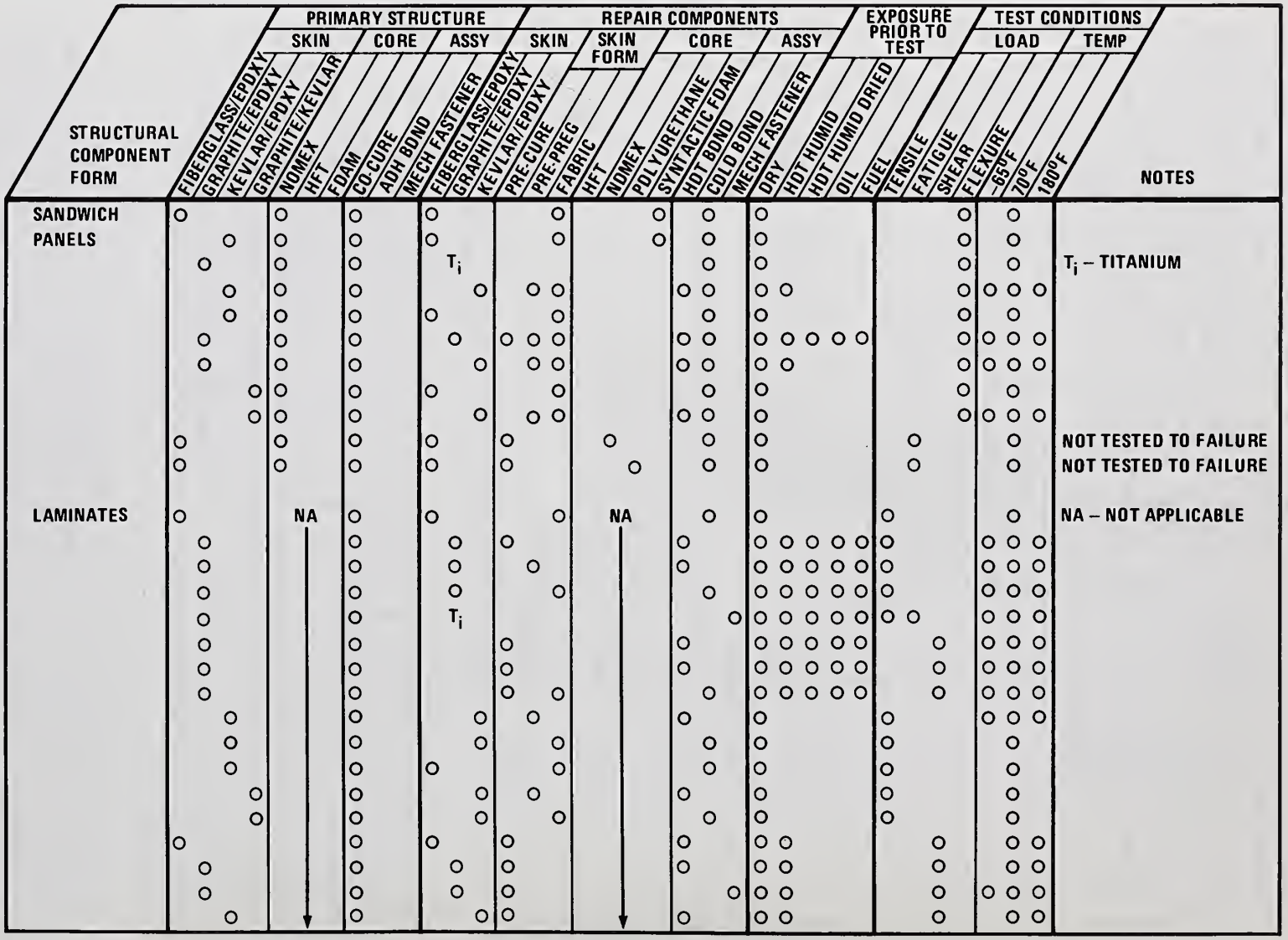


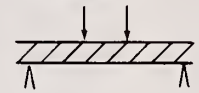
Table 2. Specimen Matrix

SPECIMENS: STRUCTURAL COMPONENTS/ CONSTRUCTION FORMS		METHODS OF ASSEMBLY: I CO-CURING, II ADHESIVE BONDING, III MECHANICAL FASTENERS	MATERIALS (1): KEVLAR/EPOXY	MATERIALS (1): GRAPHITE/EPOXY	MATERIALS (1): HYBRID/EPOXY	MATERIALS (1): FIBERGLASS/EPOXY	MATERIALS (1): HFT	CORE MATERIALS: NOMEX HONEYCOMB	CORE MATERIALS: POLYURETHANE FOAM	CORE MATERIALS: SYNTACTIC FOAM	ADHESIVE TYPES: FILM	ADHESIVE TYPES: ELEV TEMPERATURE	ADHESIVE TYPES: ROOM TEMPERATURE	MATERIAL FORMS: FABRIC	MATERIAL FORMS: TAPE	MATERIAL FORMS: FILAMENT	LOAD TESTS (2): SHEAR	LOAD TESTS (2): FLEXURE	LOAD TESTS (2): COMPRESSION BUCKLING	NOTES
SKINS																				
1	SANDWICH PANELS	I	*	*			○	*			*				*			*		
2	SANDWICH PANELS	II			○			○			○			○				○		
3	SANDWICH PANELS	I			*		○	*			*			*	*			*		
4	STIFFENED PANELS	I	○								○				○		○			
5	STIFFENED PANELS	I			○						○				○		○			○
6	STIFFENED PANELS	II			○						○			○	○		○			○
7	MONOLITHIC	I	*	*	*						*				○		*			
8	MONOLITHIC	I			○						○			○	○		○			
FRAMES																				
9	MONOLITHIC/MONOLITHIC	I		◒	◓						○		◒	◓				○		
10	MONOLITHIC/SANDWICH	II	○				○				○				○			○		
11	MONOLITHIC/MONOLITHIC	II			○						○				○			○		
12	HYBRID/SANDWICH	I			○			○			○				○			○		
13	SANDWICH/MONOLITHIC	II			○		○				○			○	○			○		
STRUCTURAL FITTINGS																				
14	SANDWICH/SANDWICH-BOLT	III	○				○				○				○		○			
15	MONOLITHIC-HINGE	III			○						○			○			○			
16	HYBRID/MONOLITHIC-DZUS	III			○						○			○	○		○			
17	SANDWICH-TIE DOWN	III	○				○				○				○			○		

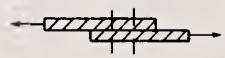
CODE
◒ WEB ◓ SKIN

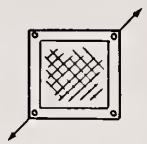
(1) HYBRID = KEVLAR & GRAPHITE

(2) LOAD TESTS
FLEXURE



SHEAR





COMPRESSION BUCKLING

generally lower than 100 percent of baseline strength. A number of tests under this condition showed as much as 50 per cent loss of strength.

Approach to solution: Further testing is recommended in several areas, such as, (1) cold bonding repairs - sandwich panels of glass and Kevlar and hybrids varying temperature and test conditions to evaluate other repair materials/ adhesives, (2) hot bonding repairs - panels with varying temperature and test conditions to evaluate repair materials/ adhesives, (3) core repairs - to determine correct foam density and flexure tests for core replacement, (4) structural fittings - fabricated from sandwich/laminate and laminate/laminate both attached with mechanical fasteners, and (5) frames - from several materials.

A typical preliminary test plan outline is offered for conducting the necessary laboratory investigations:

a) fabrication of representative structural elements
b) structural integrity tests to determine baseline strength
c) simulate damage
d) application of damage assessment techniques
e) repair
f) retest

Specifically:

a) Fabrication - A sufficient number of specimens should be fabricated to represent the spectrum of various types of structural specimens.

b) Structural Integrity Tests - Specimens representative of skins, frames, longerons and structural fittings should be tested to determine their undamaged structural capabilities at various environmental conditions.

c) Simulated Damage

(1) damage from the structural integrity tests

(2) simulated operational damage, normal "wear and tear", environmental damage

(3) simulated and/or actual ballistic damage

d) Damage Assessment - Damage assessment techniques should be applied to evaluate the severity of the damage and to permit preparation of inspection manuals.

e) Repair - each specimen, if repairable, should be repaired. The procedure should be documented for each type of specimen.

f) Retest - The specimens should be retested as per b) above to determine the quality and integrity of the repair.

g) Documentation - satisfactory repair methods should be documented, suitable for operational repair manuals.

Summary: Structural repair methods, materials, and techniques have been developed for field level repairs using cold bond (room temperature) cures. These room temperature cures, although demonstrated to be adequate in normal temperature and humidity environments, lost as much as 50 percent of their baseline strength when tested at elevated temperatures and high humidity conditions. Secondary structure and rotor blade fairing repairs using room temperature cures are acceptable for the allowed (lightly loaded) repair areas. High temperatures weakened the bonding adhesive in the repaired area resulting in premature shearing of both laminate and sandwich panels. The 350°F autoclave repair method proved to be the most effective at high temperature conditions.

Hybrid constructions of materials such as graphite reinforced fiberglass or Kevlar designs to control stiffness while providing high strength to weight ratio will require unique repair and quality control methods. Aircraft structural areas such as frames and mechanically fastened joints require development to define repair methods and procedures. The approach presented is one way, and by no means the only way, of advancing the state-of-the-art in advanced composite repairs both to broaden the existing base as well as to begin exploring new aircraft concepts and applications as the use of hybrid materials widens.

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DESIGN GUIDELINES FOR AVIONIC CORROSION PREVENTION AND CONTROL

Albert F. Carrato
George E. DeLong
Resource Management Systems
1250 Sixth Avenue, Suite 300
San Diego, California 92101

Irv S. Shaffer
Naval Air Development Center
Warminster, Pennsylvania 18974

Abstract: There is evidence that moisture intrusion currently is the largest single cause of Navy avionic (airborne electronic) equipment becoming non-operational while installed in carrier aircraft. The basis of this failure mode includes not only the general severity of the naval marine environment, but particularly the intrusiveness of the chloride-ion laden moisture that permeates the interior of the aircraft — including entering equipment housings, connectors and almost all areas generally considered to be "protected." Equipment designed for optimum electrical performance during the time it is operating can be particularly vulnerable to corrosion during the other 95% of the time when it is in a static, non-operating condition. Fundamental to the continuing nature of the design characteristics that permit such equipment deterioration is the lack of feedback information on fleet failure modes to the original equipment designer. Seldom is the original design engineer appraised of the design-induced problems he had created several years previously. Understandably, therefore, he incorporates the same design characteristics in his following assignments.

Key words: Avionic component design; avionic corrosion damage; corrosion damage; equipment design failures; marine environmental factors; moisture intrusion in avionic equipment.

1. INTRODUCTION

Avionic equipment comprises the very heart of the remarkable sophisticated capabilities designed into the current U.S. Navy combat aircraft. Consistently, however, the reliability of such avionic equipment, when deployed in fleet service, is significantly below that predicted during the design and contractual demonstration phases. Military Specifications, Military Standards and Military Handbooks describe the design characteristics of various components that are to be used in new avionic

equipment. There are laboratory tests designed to demonstrate the capability of the assembled equipment to meet prescribed requirements relative to shock, vibration, salt spray, temperature electromagnetic interference and other characteristics that can be quantified and objectively measured. These design and test requirements, however, have not been adequate to preclude the recurring and ever-increasingly costly failures when avionic equipment is operated and maintained in the U.S. Navy's fleet environment.

There is evidence that the major unforeseen avionic equipment failure mode in this fleet environment is corrosion. While the "real world" fleet environmental factors are difficult-to-impossible to duplicate in the laboratory, it is possible to minimize avionic equipment susceptibility through enlightened design once the factors are recognized and understood. There are many design decisions to be made in the development of new avionic equipment that are not constrained by Military Specifications. An understanding of the characteristics of the fleet environment which, heretofore, has not been known by the design engineer, can permit consideration of such degrading factors and provide the basis for enhanced life-cycle reliability.

The fundamental source of corrosion problems in avionic equipment is due to moisture and fluid intrusion throughout naval aircraft, especially those operating in the harsh marine environment aboard aircraft carriers and low-freeboard destroyers. The moisture and fluid intrusion, coupled with widely varying conditions involving temperature and pressure cycling, humidity, dust and dirt, industrial pollutants in the atmosphere, salt air, and stack (combustion) gases, are environmental conditions that have not been adequately recognized in avionic system and equipment design.

The degree of corrosion damage caused by moisture and fluid intrusion is compounded by five "real world" factors. The first factor is the prolific use of galvanic couples in circuitry, interfacing wire harnesses, equipment enclosures, ground and bonding junctions, and hardware mounting. The second factor is that airframe environmental integrity is an assumption rather than a fact. Recent studies by the Navy, on-site investigations at the user level, and quantitative maintenance data show a significant number of avionic systems and equipment failures are a direct result of moisture and fluid intrusion caused by poor environmental integrity of the airframe. The third factor is equipment environmental integrity. Equipment enclosures are not designed to withstand the lack of airframe environmental integrity and the results are disastrous to the contained circuitry. The fourth factor is the lack of consideration for the impact of the operational and maintenance environment on equipment design. Avionic systems and equipment are designed for optimum performance during in-flight conditions with little consideration for the fact that most equipment spends 95% of the time in a static, non-operating condition. It is during the ground maintenance time that the installed avionic system experiences a major impact from

moisture and fluid intrusion and, subsequently, corrosion damage. Any maintenance man can attest to the problems encountered during the maintenance cycle, but design engineers do not recognize the existance and the impact of these conditions during the design phase. The last, and probably the most important, factor is the lack of feedback information on failure modes to an equipment design engineer. Even when an engineer previously has designed similar equipment he is seldom aware of the failure modes experienced by his earlier equipment when deployed in the fleet environment. In most cases corrective action is performed by other activities, or a different group within the original contractor's organization. Since the original design engineer is not appraised of the design-induced problems, years later he perpetuates a faulty design. When an original designer cannot get viable feedback on his own design, what chance is there to get useful data on design weaknesses in similar equipment, but designed by other contractors?

2. GALVANIC COUPLES

The design of modern avionic systems and equipment includes a wide proliferation of metals not normally considered for use in airframe structures. Some of the rarer metals are found in the discrete circuit components such as those used in the manufacture and assembly of miniature and microminiature, integrated, and hybrid circuits. Gold is traditionally considered the best coating for corrosion resistance and solderability and silver is commonly used as a protective coating where conductivity is a requirement. Magnesium is used in applications requiring low weight-to-strength ratios. The more common metals, such as iron, steel, aluminum, copper, etc., are, of course, the mainstays in avionic equipment designs. The following is a brief list of the metals and their uses in avionic equipment:

a. Gold is common in electrical connector pins, edge connectors, leaf-type relays, miniature coaxial connectors, printed circuit board runs, semi-conductor leads, and microminiature and hybrid circuits.

b. Silver is commonly used as a protective coating on relay contacts, waveguides, wire, high frequency cavities, tank circuits, RF shields and RF gaskets.

c. Magnesium alloys find high use for antenna dishes and lightweight structures such as hardware, chassis, supports and frames.

d. Iron and steel (ferrous alloys) are used as component leads, magnetic shields, transformers, brackets, racks and general hardware.

e. Aluminum and aluminum alloys are widely used as equipment housings, chassis, mounting racks, supports, frames and electrical connector shells.

f. Copper and copper-based alloys are generally used as the base metal in edge connectors, contacts, springs, leads, connectors, printed

circuit boards and wire.

g. Cadmium is used to coat ferrous hardware, such as bolts, washers, screws and electrical connectors that come in contact with other metals.

h. Nickel and tin-plating are used for protective coatings and for compatibility purposes. Tin is widely used in solder and tin-plating is common in RF shields, filters, small enclosures and automatic switching devices.

These metals, common and exotic, combine to form literally thousands of galvanic couples, or cells, within a complex avionic environment. It is obvious that the potential for galvanic corrosion is an inherent design characteristic. Exposing these galvanic couples to the assumed "normal" environment wherein there is seldom a significant amount of electrolyte (chloride-ion laden moisture) present would not cause a major problem, but when the unpredicted element of moisture and fluid intrusion enters, created by maintenance and/or flight requirements and poor airframe environmental integrity, the results are disastrous. A good example is the use of gold plating. When an excessively thin (porous) layer of gold plating is placed directly on a ferrous substrate, in the presence of an electrolyte, corrosion always is the result!

3. AIRFRAME ENVIRONMENTAL INTEGRITY

Given the high use of dissimilar metals in the design of avionic equipment, an assumption by the avionic design engineer — based upon an interpretation of a Military Standard that the airframe environmental integrity will continuously protect the avionic equipment — is critical to the reliability and maintainability of avionic equipment design. Unfortunately, however, on high speed carrier aircraft and helicopters there is no such thing as a watertight airframe. The high degree of flexure of the airframe precludes effective sealing of equipment bay doors, access panels, doors, steps, canopies, windows, vents, ducts, static pressure sensors, and other fuselage openings. The "form-in-place" seals and gaskets have not been designed that will withstand this in-flight flexure. In the case of helicopters, there has never been an airframe built (to date) that does not have water intrusion as a primary problem in the fleet environment. Naval aircraft are generally susceptible to moisture and fluid intrusion originating from the following sources:

a. Rainstorms
b. Water washdown systems
c. Hand washing evolutions
d. Salt water inundation
e. Environmental control systems
f. Hydraulic, fuel, engine oil, anti-icing, and coolant line leaks
g. Condensation from cyclic temperature and pressure variation
h. Low-level over-water flight

i. Emergency firefighting materials
j. Solvents, detergents, strippers and other cleaning materials.

The avionic system in a modern aircraft is not a series of isolated "black boxes" sealed against the environment. There are many components, relays, terminal boards, circuit breaker panels, switches, antennas, lights and other hardware that make up a complete avionic system. A sophisticated aircraft contains miles of electrical wire, extensive coaxial cables, hard lines, waveguides, and hundreds of electrical connectors. That same aircraft contains hydraulic lines, oil lines, fuel lines, cooling air ducts, flight control linkages, and control rods. When water penetrates the airframe these lines and cables become "moisture and fluid conduits" that carry the insidious electrolyte directly to the avionic equipment and components. A simple hydraulic line can direct water many feet through the airframe and deposit the water on equipment and components that are assumed to be in a protected area of the airframe. A wire bundle can carry moisture or water directly into the back of an electrical connector, through the connector and into the avionic equipment housing. Just as moisture and fluid intrusion and moisture conduits are inherent in aircraft design, there is another problem of water-traps. Moisture, water and fluids pool in water-traps or "bathtub" areas and are especially damaging to avionic equipment installed in these areas. The bilge area of the airframe is particularly susceptible to this condition, and it is in this area where cable runs, wire bundles, coaxial cables, lights and antennas are installed. It is almost impossible to seal the equipment and components in this area against moisture and fluid intrusion because of requirements for maintenance access. Thus, it is these components that are exposed to the "bathtub" areas where corrosion is particularly evident. Even though the bilge is a rather obvious problem area, there are other areas of concern, such as structural stringers, ribs, bulkheads, shelving, etc.

4. EQUIPMENT ENVIRONMENTAL INTEGRITY

Avionic equipment must be designed with consideration for the presence of moisture and fluids. The environmental integrity of the equipment enclosure must be evaluated in relation to the ultimate installation in the airframe with consideration for cooling air, weight, space, etc. Long ago pressurized equipment was identified as too heavy, but it is the only equipment design that has displayed the ability to withstand the marine environment. Recent investigations of U.S. Navy front-line aircraft show the following equipment design deficiencies are common:

a. Equipment lids that contain holes for cooling air. These holes become sources for moisture intrusion.

b. Screws and hardware that are installed in dimpled or countersunk areas on top of equipment lids. These areas become water-traps and sources for moisture intrusion.

c. Drain holes installed in the bottom of avionic equipment housings. These drain holes become a problem when the equipment stands in water-trap or bathtub areas. There are also cases where equipment later is mounted in some other type of airframe with the drain holes now facing up, creating an obvious problem.

d. The use of foam material in the lids of equipment that reverts as a result of a combination of temperature, pressure and moisture intrusion.

e. The use of foam in the lid of equipment designed to hold down circuit cards where the top of the circuit card contains electrical "test points." This practice becomes a problem when the foam acts as a sponge, holding moisture which results in corrosion across the "test points," and creates short circuit conditions.

f. The use of wire-wrap "mother" boards mounted in the bottom of avionic equipment containing drain holes. When moisture is present the result is corrosion on the wire-wrap "mother" board. This creates a problem in that it is essentially impossible to clean or remove corrosion from wire wrap.

g. Equipment designs where one element in the equipment requires barometric pressure, yet the whole equipment is exposed to the ambient environment.

h. Electrical connectors mounted vertically, vice horizontally, on equipment housings.

i. The use of direct-air cooling systems where air is channeled directly onto active electronic components and circuit cards. This is a high source of direct water intrusion, especially where salt-laden ram air is channeled from outside the aircraft for emergency cooling purposes.

j. The use of conductive gaskets impregnated with silver, gold or graphite as lid and enclosure environmental seals. These gaskets create gross galvanic corrosion when they are in contact with the aluminum enclosure surfaces.

The steps taken to solve the problems of poor equipment and airframe environmental integrity could be considered comical, were it not for the immensity of the problem. Modern aircraft now have curtains installed in airframe and cockpit areas designed to shunt water around equipment and control boxes. Drip pans and drain lines are installed to catch water that would otherwise inundate equipment. RTV (Room Temperature Vulcanizing) sealants, which are highly susceptible to hydraulic fluid and coolant fluid, are being used to seal electrical connector back shells and equipment housings against moisture. Last, but not least, numerous drain holes are being placed in airframe structures, radomes,

antenna housings, etc., in order to drain water. Unfortunately, they become sources of moisture entry during water washdowns, splashing from wet runways, etc.

This paints a grim picture for the design engineer, but, unfortunately, there is still more to consider.

5. OPERATIONAL AND MAINTENANCE ENVIRONMENT

The operational and maintenance environment has a number of characteristics which should be recognized in the design of avionic equipment. Military Specifications (and other design specifications and standards) imposed on the avionic design engineer dictate that avionic equipment perform at its optimum during in-flight conditions. The problem with this premise is that avionic equipment spends approximately 95% of the time in a static, non-operating condition. Most U.S. Navy front-line combat aircraft average between one-to-two hours per day in flight and the remainder of the time in maintenance or a static condition. In some cases an aircraft may be non-operational for many weeks while awaiting parts. During these periods the aircraft may be "unbuttoned" to facilitate maintenance; canopies, radomes, equipment bays, doors, etc., opened and avionic equipment removed. This results in electrical connectors, wire bundles, equipment racks, control boxes, circuit breaker panels, relays, antennas, and the multitude of other avionic components in the aircraft being exposed to salt air, moisture, stack and industrial gases, dirt, dust, and other environmental factors that cause corrosion damage in the equipment. This is a "real world" condition that constitutes the vast majority of the operational and maintenance environment. It is not adequately recognized by design specification, testing requirements or avionic system and equipment design engineers.

The following are some examples of the operational and maintenance environment that require consideration by the design engineer:

a. During fresh water washdown the high pressure water washdown system deluges the aircraft with tremendous amounts of water, from all directions, in a very short period of time. Clamshell doors on helicopters and equipment bay doors on fixed wing aircraft leak like sieves when gaskets become worn or damaged. Exhaust fan inlet and ram air cooling ducts, vapor exhaust ports, cockpit canopies, even the simple molded step (helicopters) that are designed without a self-sealing mechanism, become entry areas for water intrusion. The external bulkhead electrical connectors, external wire and cable runs, antennas, control linkages and other such areas where the shell of the fuselage is penetrated are potential points for water intrusion.

b. Rainstorms create a similar water intrusion problem and, as stated previously, the flexure of the airframe essentially ensures water intrusion around access panels and doors. Of course, water intrusion is especially severe to avionic equipment and components mounted external

to the airframe, such as: electronic countermeasure pods, photographic pods, refueling stores, bomb and missile racks, lights, antennas, and wheel well areas.

c. Environmental control systems add another facet to the overall problem of moisture and fluid intrusion in the maintenance environment. During flight (a relatively small part of the life of the equipment), the avionic equipment is protected by the dry conditioned air provided by the environmental control system. This is not the case during the time the equipment spends on the flight-line or flight deck, however. Here the equipment is exposed for a much longer period of time to a completely different and harsher environment. In those instances where environmental cooling is required for ground operation and ground cooling units are available, the environmental cooling system may, in fact, induce moisture by the introduction of cool air directly into the warm humid area of the avionic equipment, thus causing condensation.

d. Leaks in hydraulic lines, fuel lines, coolant lines and oil lines are other common sources of fluid intrusion in avionic equipment. Each of these fluids has the potential for adverse reaction with various organic materials in the aircraft. Some fluids may, for example, attack the adhesion of protective organic finishes, soften potting compounds, cause undue seal and gasket swelling, or attack wire and coaxial cable insulation. Damage to these organic materials generally results in increased susceptibility to corrosion.

e. The storage and transportation of avionic equipment between supply facilities, work spaces and the flight-line or flight deck is continually suspect. Depending on the locality, the equipment can be exposed to very harsh environmental conditions. It is not uncommon to find sophisticated avionic equipment temporarily stored behind the "island" on a carrier flight deck where it is exposed to salt air, stack gases, etc. On carriers and "LAMPS" destroyers, avionic equipment is stored on the hanger deck where it is constantly exposed to moisture laden salt air. Occasionally, equipment on the hanger deck is exposed to sloshing water that can occur during operations in rainstorms, high winds and high seas.

f. Maintenance publications intended to support specific equipment seldom recognize the potential corrosion problem, and essentially never call out the proper use of the best anti-corrosion materials. The "fly-to-failure" maintenance philosophy applied to most avionic equipment limits maintenance as a practical means to compensate for inadequate corrosion resistant design.

6. EFFECTS OF CORROSION ON AVIONIC COMPONENTS

Corrosion attack on the various elements that make up the total avionic systems costs millions of dollars worth of maintenance manhours and replacement parts, plus a reduction of aircraft system availability.

Table 1 summarizes the effects of corrosion on avionic components. The following discussion is intended to highlight the specific design problems that cause corrosion damage in present day avionic systems, equipments and components.

Automatic direction finder, doppler and numerous blade antennas are usually mounted in bilge areas. Water becomes entrapped in the bilges by stringers causing water "pools" to form around antenna coax leads. This entrapped water penetrates through to the antenna base/fuselage skin interface and sets up a corrosive condition with the antenna gasket, antenna housing and aircraft skin. Fiber gaskets act as sponges, holding moisture between the antenna and skin. Much worse, though, are the conductive gaskets impregnated with graphite, silver or copper. These gaskets, placed between bare aluminum skin and the aluminum antenna to enhance conductivity, create a galvanic corrosion condition that not only precludes the enhanced conductivity, but causes the antenna to require frequent replacement. Antenna electrical connectors and coaxial connectors in the bilge areas are corrosion prone because of the continual presence of entrapped water. In addition, access to interior connections of many blade and flush-mounted belly antennas for the purpose of inspection or corrosion control is not feasible. Radomes in the lower fuselage or nose section are a major problem. The inadequate use of sealants, poor gasket design and drain holes allow the intrusion of the corrosive environment. Where metal-to-metal contact is present, especially if a bimetallic condition exists, the contacting parts are highly corrosion-prone. Mounting hardware, including screws, nuts, bolts, etc., on antennas in radomes and on the lower fuselage is an example of this problem.

Considering the large number of electrical connectors in a modern avionic system, the connector corrosion problems are "mind-boggling." Since fluid intrusion frequently allows moisture to be present in a connector, it is evident the state-of-the-art electrical connectors are not really "environmentally sealed." The following electrical and coaxial connector corrosion problems are considered commonplace in naval aircraft:

a. Electrical connectors that are externally mounted in the air stream are degraded by erosion of the external protective coatings with subsequent corrosion of the base metal.

b. Electrical and coaxial connectors mounted horizontally are susceptible to water intrusion through the rear section when attaching cables do not contain a "drip loop."

c. Bayonet-type electrical and coaxial connectors mounted vertically are susceptible to degradation due to fluid entrapment around the base of the connector from standing water and/or hydraulic fluid.

d. Externally mounted electrical connectors hidden by fairing covers

Table 1. Effects of Corrosion on Avionic Components

COMPONENT	FAILURE MODE
ANTENNA SYSTEMS	Shorts or changes in circuit constants and structural deterioration.
CHASSIS, HOUSINGS, COVERS, AND MOUNTING FRAMES	Contamination, pitting, loss of finish and structural deterioration.
SHOCK MOUNTS AND SUPPORTS	Deterioration/loss of shock effectiveness.
CONTROL BOX MECHANICAL AND ELECTRICAL TUNING LINKAGE	Intermittent operation and faulty frequency selection.
WATER TRAPS	Structural deterioration.
RELAYS AND SWITCHES	Mechanical failure, shorts, intermittent operation and reduced system reliability.
PLUGS, CONNECTORS, JACKS AND RECEPTACLES	Shorts, increased resistance, intermittent operation and reduced system reliability.
MULTI-PIN CABLE CONNECTORS	Shorts, increased resistance, intermittent operation and water seal deterioration.
POWER CABLES	Disintegration of insulation and wire/connector deterioration.
DISPLAY LAMPS AND WING LIGHTS	Intermittent operation, mechanical and electrical failures.
WAVEGUIDES	Loss of moisture integrity, pitting, loss of efficiency and structural deterioration.
RADAR PLUMBING JOINTS	Failure of gaskets, pitting and power loss.
PRINTED CIRCUITS AND MICROMINIATURE CIRCUITS	Shorts, increased resistance, component and system failures.
BATTERIES	High resistance and failure of terminals, and structural deterioration of mounting.
BUS BARS	Structural and electrical failures.
COAXIAL LINES	Impedance fluctuations, loss of signal and structural deterioration of connectors.

are prone to extensive corrosion damage because they are not visible for routine inspection and, therefore, timely corrective action.

e. Vertically mounted external electrical connectors on the upper fuselage transmission area of helicopters are susceptible to water entrapment at the base and rear of the connectors.

f. Supposedly environmentally sealed connectors on the engine, transmission, constant speed drive and hydraulic compartments are subject to damage of the environmental seal by hydraulic fluid, fuel and cleaning solutions. Numerous connectors in these areas are potted to eliminate this problem.

g. High density environmental electrical connectors are subject to seal damage and loss of integrity when maintenance personnel replace pins with pin insertion and removal tools.

Although definitive maintenance failure documentation has not been available in the Navy Maintenance Data Collection System (MDCS) to support this allegation, it appears that a consensus of avionic maintenance engineers and technicians are beginning to support the thesis that a large percentage of in-flight avionic discrepancies are attributable to moisture in electrical connectors. Over the past 20 years a high rate of anomalies, such as the "no-defect" and "phantom gripe," have occurred in the complex avionic systems or equipment. These anomalies ultimately have become an accepted "norm" in the troubleshooting and maintenance of the equipment. It is a common experience to find that the "in-flight reported" discrepancies disappear when the electrical connectors are parted and then remated during troubleshooting. Since nothing is actually seen when the connector is parted, a "no-defect" is entered in the maintenance documentation. In reality, there was a discrepancy (defect) caused by moisture, cleanable film, or a small amount of corrosion that was displaced during the parting and remating of the electrical connector. Although this anomaly has long been related to wire bundle electrical connectors and antenna coaxial connectors, it has recently been identified as a major problem on circuit card "edge connectors" within avionic equipment. A recent study of a sophisticated radar system (installed in a U.S. Navy fighter aircraft) indicates that approximately 50% of all in-flight discrepancies associated with the radar equipment are directly related to moisture and corrosion deposits on the circuit card edge connectors. In such cases the maintenance technician reseats the circuit card edge connectors prior to bench testing the specific equipment in question. This action eliminates over one-half of the reported discrepancies, as verified by the bench test. Unfortunately, neither the identification of the true problem, nor a preventive action to preclude reoccurrence, takes place in such a situation.

Wire bundles and coaxial cables are another problem area that can be categorized. As previously mentioned, a wire bundle or a coaxial cable, depending on location, can become a conduit for fluid in the airframe.

In addition, the wire bundles and coaxial cables are prone to a rather unique environmental problem — certain wire coatings are hygroscopic. It is recognized that once a wire jacket "breaks down" due to moisture, it is susceptible to a rapid deterioration. Older helicopters show a high degree of corrosion in wire bundles behind the nose clamshell doors. This problem is usually evidenced by the wire run turning green under the protective coating. An associated problem is the possibility that the wire jacket may deteriorate in the presence of the aircraft cleaning compounds. Investigations have shown that certain types of wire jackets are susceptible to major deterioration due to the alkalinity (high pH) of the detergents normally used to clean the aircraft. This problem is particularly prevalent in wing fold, wheel well and other areas exposed during aircraft cleaning evolutions. Understandably, this problem can become highly critical wherever water intrusion occurs. It takes little imagination to envision the consequences should a high pH solution remain in contact with an internal wire bundle for any period of time. The following are additional corrosion problems associated with wire bundles and coaxial cables:

a. Braided fiber wrapping for abrasion resistance on coaxial cables acts as a wick to lead water and other fluids into associated connectors.

b. Environmental seals on electrical connectors are damaged by loads imposed during flexing of wire bundles, permitting water intrusion past the damaged seals.

c. The wire bundles in external stores pylons are exposed to engine cleaning compounds, particularly on helicopters. These compounds saturate the wiring and connectors, thus damaging the integrity of the protective coatings.

d. The wire bundles and electrical connectors in the vicinity of the engine exhaust gases are prone to accelerated corrosion damage due to heat and additional elements such as sulfur that are contained in the exhaust gas.

e. On helicopters, the cargo hook controller and rotor blade wire bundles, with their associated electrical connectors, are in a highly corrosive environment.

Cockpit and cabin areas exposed to moisture intrusion through open canopies, cabin doors and windows. Most control boxes are susceptible to corrosion damage internally, especially those exposed to direct water impingement. In addition, the back of instrument panels are normally hidden from view. The numerous bimetallic couples and difficulty of inspection result in considerable corrosion damage. In the case of helicopters, the emergency ram air cooling ducts create an additional corrosion problem on the back of instrument panels. All aircraft consoles use dissimilar metals fasteners, screws and nut blocks to secure instru-

ments, thus creating galvanic couples.

Circuit breakers, relay racks and terminal boards also are prone to corrosion due to the dissimilar metals construction and exposure to moisture intrusion. Circuit breaker panels mounted in the overhead of helicopters are especially susceptible to water intrusion. Water enters through skin seams, windscreen edges and through upper fuselage skin penetrations for actuators, cables, etc. The water migrates onto the back of the circuit breaker panels via cable conduits and initiates the corrosion process with little chance of visual detection until it is too late.

Radar waveguides, couples and joints are susceptible to corrosion damage due to moisture intrusion and dissimilar metals couples. As previously discussed, the waveguide is a natural fluid conduit. When water runs along a waveguide it causes corrosive attack at the waveguide couples and joints, and without good preventive measures, may enter the waveguide flange causing serious degradation of the signal. The pressurized waveguide appears to be the best design to preclude these problems because a pressurization loss is an immediate warning of loss of integrity.

Avionic equipment shock mounts, racks and associated hardware are normally constructed of dissimilar metals and are relatively inaccessible for inspection and timely corrosion control. Associated with this problem is the grounding strap, which normally is used to bond the rack, shock mount, or an actual piece of equipment electrically to the airframe. The washers, screws and grounding straps usually create a dissimilar metals or galvanic couple. The slightest amount of corrosion at any point of mating (where dissimilar metals come in contact) can cause electromagnetic interference (EMI). This problem is especially critical in the more sophisticated avionic systems found in modern aircraft.

Lighting system failures due to corrosion run high during shipboard operations where the light and its associated plug are susceptible to the harsh salt-air environment. The slightest moisture intrusion creates a corrosion product between the bayonet-type bulb base and socket, creating a loss of electrical contact (or ground). This problem is prevalent in all external light systems, such as wing lights, formation lights, approach lights, etc.

7. DESIGN FEEDBACK ENHANCEMENT

From the standpoint of the avionic design engineer, there is a real problem of determining what features of his new design might be a source of corrosion problems. Obviously, designing equipment to the present available Military Specifications and testing based on laboratory situations vice the "real world" environment discussed here are not adequate to ensure the newly designed equipment will be capable of existing in the environment in which it must function.

Feedback appears to be the missing link. A program intended to produce design guidelines relative to the marine environment for the avionic design engineer presently is being conducted by Naval Material Command and Naval Air Systems Command. This program is sponsored by Mr. A. J. Koury (NAVAIR Code 4114C) and has shown that the avionic design industry, as a whole, is lacking feedback data on the failure modes that are occurring in the fleet environment. This factor appears to be the loophole in the present information system for the design engineers attempting to produce equipment without reliability and maintainability problems associated with corrosion.

Presently there are two sources of feedback information available to the design engineer. One is quantitative and the other is qualitative. The quantitative source is the maintenance failure data available through the various U.S. Navy maintenance data collection systems, such as:

a. Maintenance Data Collection System (MDCS)
b. Computerized Unsatisfactory Report Engineering System (CURES)
c. Analytical Maintenance Program Analysis System (AMPAS)
d. Depot Maintenance Data Collection System (DMDCS)
e. Navy Safety Center failure data

These data sources provide valuable feedback of a general nature, but also can provide definitive information if the user has a good understanding of how the data is formulated by the avionic maintenance technician. Tables 2, 3 and 4 are samples of MDCS data on three types of aircraft: a front-line fighter aircraft, an advanced ASW aircraft, and a sophisticated attack aircraft. Each table was constructed from MDCS data covering a period from November 1979 through October 1980. In all cases the "documented corrosion repair manhours" are those manhours expended by the avionic maintenance technician in repair or correction of a corrosion related discrepancy on the specific avionic system. The malfunctions analyzed were: corrosion, wet, weather, contamination (moisture and fluid), dirty, and delamination.

Table 2. Fighter Aircraft Documented Annual Avionic Corrosion Manhours

System	Documented Corrosion Repair Manhours
Power Supply/Wiring	3,558
Lighting	636
Instruments	1,830
Flight Reference	680
Flight Controls	558
Communications	611
Interphone	224

Table 2. Fighter Aircraft Documented Annual Avionic Corrosion Manhours (Cont)

System	Documented Corrosion Repair Manhours
IFF	250
CNI Package	190
Radio Navigation	547
Radar Navigation	176
Bombing Navigation	125
Weapons Control	8,081
ECM	833
TOTAL	18,299

Table 3. ASW Aircraft Documented Annual Avionic Corrosion Manhours

System	Documented Corrosion Repair Manhours
Power Supply/Wiring	4,301
Lighting	586
Instruments	594
Flight Reference	349
Flight Controls	811
Communications	491
Interphone	1,033
IFF	279
CNI Package	44
Radio Navigation	333
Radar Navigation	742
Bombing Navigation	4,004
Weapons Control	114
ECM	592
TOTAL	14,273

Table 4. Attack Aircraft Documented Annual Avionic Corrosion Manhours

System	Documented Corrosion Repair Manhours
Power Supply/Wiring	10,116
Lighting	2,657
Instruments	2,332
Flight Reference	357
Flight Controls	352
Communications	1,465
Interphone	1,143
IFF	761
CNI Package	1,029
Radio Navigation	520
Bombing Navigation	3,091
Weapons Control	2,716
ECM	4,953
TOTAL	31,492

Table 5 shows a summary of the documented avionic corrosion on the same three aircraft and includes the cost of the maintenance manhours. This table includes the "documented support action manhours" which are those manhours expended in cleaning and preservation of the avionic systems. Most design and maintenance engineers responsible for avionic equipment in modern naval aircraft tend to consider the failure data provided by the fleet maintenance technician to be somewhat less than definitive. Interestingly, in all three aircraft shown in Tables 2, 3 and 4, the aircraft power supply and wiring are high manhour consumers in relation to the other systems. This problem has consistently plagued the avionic maintenance technician and is obviously reported. Every new aircraft delivered to the U.S. Navy continues to exhibit high manhours expended in wiring, connectors and power supply system. One wonders why? From a morale standpoint, if nothing else, the maintenance man who continuously generates the maintenance data would like to see some evidence that someone is using the data as a guide to problems requiring solutions.

It should be noted that the "documented support action manhours" exceeds the "documented corrosion repair manhours" in all three sample aircraft. This is a direct indication that the avionic maintenance technician is spending a good deal of maintenance time battling the corrosive effects of the environment. It is obvious that the MDCS data bears out the fact that avionic corrosion does exist. It goes without saying that $3,000,

000 in annual manhour cost is not a small problem, but what good is this kind of data to the avionic design engineer?

Table 5. Documented Annual Avionic Corrosion Summary

Aircraft Type	Average Number of Aircraft	Documented Corrosion Repair Manhours	Documented Support Action Manhours	Total Corrosion Manhours	Annual Cost
Fighter	194	18,299	21,642	39,941	$ 665,000
ASW	124	14,273	30,359	44,632	744,000
Attack	259	31,492	64,026	95,518	1,591,000
Totals	577	64,064	116,027	180,091	$3,000,000

The design engineer must consider two points in his new design:

a. Is the new system or equipment similar to a previous design by the engineer or his company?

b. Is the new system or equipment similar to any previous design presently used in fleet aircraft built by another company?

In the case where designs of avionic equipment that are similar to equipment previously designed by the engineer (or another engineering group in his company) the problem of acquiring the failure data on the previous design would appear to be relatively simple. Unfortunately, this seldom seems to be the case. Usually, the original designer of individual avionic equipment is a subcontractor to the prime contractor of an aircraft, or avionic system for an aircraft. The "feedback" loop for failure data relative to corrosion in avionic equipment appears to be relatively limited from the prime-to-subcontractor on previous system designs unless the original design is a complete failure and requires a redesign or retrofit. But even with the breakdown in the "feedback" loop, the quantitative maintenance failure data is available and the design engineer, or his company, can acquire the data to show previous failure modes in similar designs. In the second case where a design concept is "new" to the design engineer, there is little or no formal "feedback" loop for failure data from the prime-to-subcontractor. Still, the quantitative maintenance data exists if like equipment is in use in the fleet.

This brings up the second source of maintenance data — the qualitative source. The fleet avionic maintenance technician is the primary source of qualitative maintenance failure data. He is the individual who originally documents the maintenance failure data available in the various data collection systems. The avionic maintenance technician inherently

is left "out-in-the-cold" when a new avionic system is on the drawing board, however, this intrepid individual is a fountain of knowledge, because, like any consumer in today's world, he is the ultimate user of the avionic equipment and knows, better than anyone, the shortcomings of the supposedly "state-of-the-art" equipment he deals with every day.

When the design engineer proposes to carry out a design similar to a previous design, or opts to use a new design, it is important that consideration be given to both the quantitative and the qualitative data source. The steps in accumulating the quantitative data are available through numerous U.S. Navy organizations, the prime contractor, commercial maintenance engineering consultants, etc. The qualitative source is only available through direct liaison with the fleet avionic maintenance technician. The maintenance technician not only has the background in the problems and failure modes in similar fleet equipment, but he is also able to expand upon the maintenance failure data he normally provides during the maintenance function.

An example of the input provided by the maintenance technician is highlighted by a program sponsored by Mr. A. J. Koury of Naval Air Systems Command to study "the effects of corrosion on aircraft external lights." This study required interviews with the fleet avionic maintenance technicians to determine why maintenance failure data did not reflect significant corrosion in aircraft external light systems. The study was conducted using the same fighter and ASW aircraft listed in Tables 2 and 3, plus the addition of a front-line helicopter. Initially, the MDCS maintenance failure data was reviewed in an effort to identify all corrosion related malfunctions involving external lights. The next step was interviews with the maintenance technicians in two squadrons for each of the subject aircraft.

These interviews brought to light some rather interesting facts. First, the maintenance technicians (over 25 interviewed) stated, to a man, that only one-third of the corrosion malfunctions in aircraft external lights were documented. Second, they advised that a large number of documented failures reported were not identified as corrosion failures, but were, in fact, corrosion related. Instantly, the documented corrosion problem more than tripled. The point is that the fleet avionic maintenance technician was invaluable in more accurately quantifying the available maintenance failure data and, with his input, the problem of corrosion in external light systems took on a different perspective.

Table 6 shows results of the study, with emphasis on maintenance manhours and annual cost of those manhours, for the purpose of demonstrating the cost of corrosion failures in U.S. Navy aircraft. The "total maintenance manhours" are the documented manhours expended on all external light malfunctions (including corrosion). The "corrosion repair manhours" are the documented manhours which include all malfunctions identified by the avionic maintenance technician. The "percent corrosion" relates the percent of total maintenance manhours that were

corrosion related. The "documented corrosion annual cost" is based on "corrosion repair manhours" times the cost of $16.66/mmh. The "estimated corrosion annual cost" is based on three times the "documented corrosion annual cost" figures, which resulted from the fact that all maintenance technicians interviewed indicated that 66% (two-thirds) of the problem went unreported in the MDCS system.

Table 6. Results of External Lights Corrosion Study

Aircraft Type	Total Maintenance Manhours	Corrosion Repair Manhours	Percent Corrosion	Documented Corrosion Annual Cost	Estimated Corrosion Annual Cost
Fighter	18,960	7,281	38.4	$121,000	$363,000
Helo	3,400	2,026	59.6	34,000	102,000
ASW	7,169	3,004	41.9	50,000	150,000
Totals	29,529	12,311	41.7	$205,000	$615,000

Table 7 represents the results of the same study, but now includes the corrosion manhours and annual cost of "internal and external light systems" in the subject aircraft. The interviews with the maintenance technicians indicated that the same deficiencies in maintenance failure data existed in the internal light systems as was shown in external light systems. Again, 66% (two-thirds) of the problem was not documented in the MDCS system. The figures now begin to indicate that the maintenance failure data has many hidden statements that only the avionic maintenance technician can quantify. Any assumption that the maintenance failure data is useless to maintenance or design engineers is, obviously, erroneous in terms of identification of the "real world" problems. The figures in Table 7 show approximately $1,000,000 expended annually in the maintenance manhours on corrosion related problems in "internal and external light systems." An extrapolation of the internal and external light systems in all U.S. Navy aircraft indicates that over $5,800,000 is expended in maintenance manhours on light systems alone.

Table 7. Estimated Cost of Internal/External Light Corrosion

Aircraft Type	Total Maintenance Manhours	Corrosion Repair Manhours	Total Corrosion Annual Cost	Estimated Corrosion Annual Cost
Fighter	25,712	10,284	$171,000	$ 514,000
Helo	8,520	3,408	57,000	170,000
ASW	15,812	6,325	105,000	316,000
Totals	50,044	20,017	$333,000	$1,000,000
All Navy Aircraft	294,364	118,000	$1,960,000	$5,800,000

Is there a documented and quantifiable corrosion problem in avionic systems and equipment? The answer is evident by comparing the "documented MDCS avionic corrosion manhours and cost" with the "light system corrosion manhours and cost." Table 8 demonstrates this relationship for the fighter and ASW aircraft. In Table 8, the "MDCS documented avionic corrosion" annual maintenance manhours and cost figures from Table 5 are used for the fighter and ASW aircraft. The "light system corrosion" annual maintenance manhours and cost figures from Table 7 are used for comparison. It is obvious that the "light system corrosion" data is a good percentage of the total "MDCS" data that represents all avionic systems on the subject aircraft. There are 12 to 14 avionic systems in an average aircraft and light systems are but one of those avionic systems.

Table 8. Estimated Annual Cost of Avionic Corrosion

Aircraft Type	MDCS Documented Avionic Corrosion		Light System Corrosion		Estimated Annual Avionic Corrosion	
	MMH	COST	MMH	COST	MMH	COST
Fighter	39,941	$ 665,000	30,852	$514,000	308,000	$5,000,000
ASW	44,632	744,000	18,975	316,000	189,000	3,000,000
Totals	85,573	$1,409,000	49,827	$830,000	497,000	$8,000,000

Assume for this discussion that the light systems represent approximately 10% of the total avionic corrosion problem. Based on this premise, it is evident, with simple extrapolation, that the fighter aircraft has an avionic corrosion problem that approaches $5,000,000 annually and the ASW aircraft is approximately $3,000,000 annually. Impressive? Imagine what aircraft power supplies and wiring are costing. It is this kind of feedback that is required by the design engineer; without it he is not recognizing a problem that is costing millions in maintenance manhours and avionic equipment failures caused by the lack of recognition of a "real world" problem. With the significance of a problem, defined by the MDCS data, the design engineer must now investigate the WHY of that problem, including acquisition of qualitative data as previously described. From this he can design the new equipment knowing he is not perpetuating a known weakness.

8. CONCLUSIONS

The environment in which avionic equipment exists is not presently recognized by the avionic design engineer. The Military Specifications and accepted standards for the testing of avionic equipment do not duplicate, nor even recognize in some cases, the "real world" environment. The prolific use of dissimilar metals and the lack of airframe and avionic equipment integrity against fluid intrusion have created a major cause of avionic equipment failures. These conditions are compounded by moisture conduits in the airframe and the effects of the operational and maintenance environment. This results in corrosion that may be the

primary single source of failures in avionic equipment and systems. Granted, some of the problems discussed could possibly be alleviated through the use of preventive maintenance techniques on the part of the avionic maintenance technician. The problem is that preventive maintenance has continuing costs in money and manhours. A recently completed study of "antenna system corrosion," sponsored by Mr. A. J. Koury of Naval Air Systems Command, shows that this problem consumes nearly $2,000,000 in manhours annually on front-line combat aircraft!

The operational and maintenance environment is an element of the "real world" that requires understanding by the avionic system and equipment engineer. Since avionic equipment is most subject to corrosion during the 95% of the time it is in the static, non-operating condition, it stands that this "worst case condition" is what the avionic design engineer should be working toward in preventing corrosion in new and retrofit equipment design.

In the past the avionic maintenance engineers and design engineers have stated that no data, or hard facts, exist to justify changes to standard design techniques. In light of the data collected and partially represented in this dissertation, this is no longer valid. The MDCS and other available maintenance failure data proves unequivocably that an avionic corrosion problem does exist. The design engineer must become aware of the quantitative and qualitative data sources available to him. It is imperative that the design engineer meet the maintenance technician and understand his environment, plus the effects it has on the latest equipment entering into design.

It is the authors' hopes that this discussion will prompt a serious look at the problems highlighted in the text. The fact is that the present equipment designs put responsibility for the control of avionic corrosion on the maintenance technician at this time. It appears that avionic systems and equipment could be designed with appropriate consideration for the environment in which it must exist — then the problem is solved for good!

USE & EXPERIENCE OF ADVANCE COMPOSITES REINFORCED WITH KEVLAR® IN AIRCRAFT

Paul R. Langston
E. I. du Pont de Nemours & Co., Inc.
Wilmington, Delaware, U.S.A., 19899

Kevlar® has experienced rapid growth due to its use in a wide variety of industries and applications. From its use on the ground in tires, to satellites in space and to cables on the ocean floor, scientists continue to expand its use.

Kevlar® was introduced in 1972 with a total capacity of 100,000 lbs./yr.; in 1978 we had expanded into a plant capacity of 15,000,000 lbs./yr. and now a new construction is in progress for a plant to produce 45,000,000 lbs./yr. which will be on line in early 1982.

The purpose of this presentation is to update you on the wide use of Kevlar® in industry, with emphasis on the use of Kevlar® in aircraft and aerospace.

Kevlar® is sold in three different forms. Each is developed for a particular application. (Fig. 1)

Figure 1

Kevlar® can be described technically as being 43 percent lighter than fiberglass, with a density of 1.44 g./cc. for Kevlar® versus 2.55 g./cc. for fiberglass.

Twice as strong as E-glass and 16 times as strong as aluminum on a specific tensile strength basis, the highest specific tensile strength of any commercially available fiber. Specific tensile modulus is 3x that of fiberglass and approaches that of HT graphite.

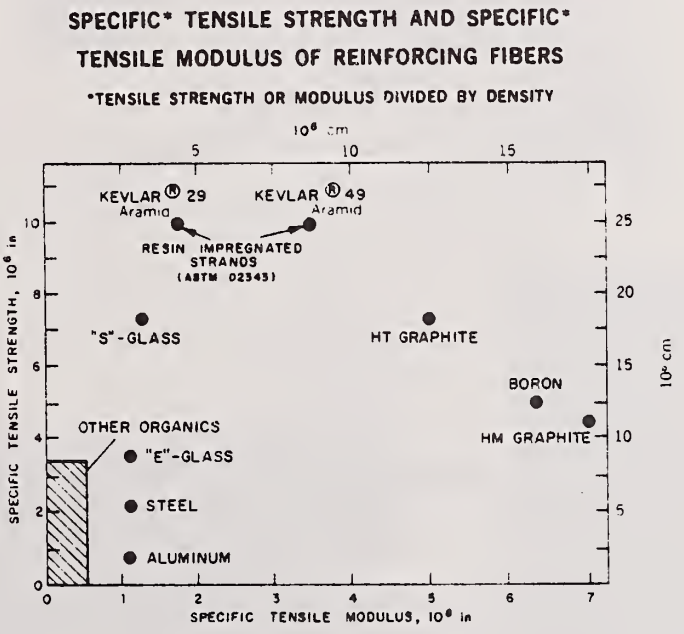


Figure 2

Kevlar® 49 displays excellent stability over a wide range of temperatures for prolonged periods. The data shown are based on a resin impregnated fiber. A composite reinforced with fabric of Kevlar® 49 would be expected to behave similarly.

Even at a temperature as low as -320°F (-196°C) Kevlar® 49 shows essentially no embrittlement or strength loss.

Kevlar® 49 also has excellent dimensional stability with a slightly negative coefficient of thermal expansion ($-1.1 \times 10^{-6}/°F$ or $-2 \times 10^{6}/°C$).

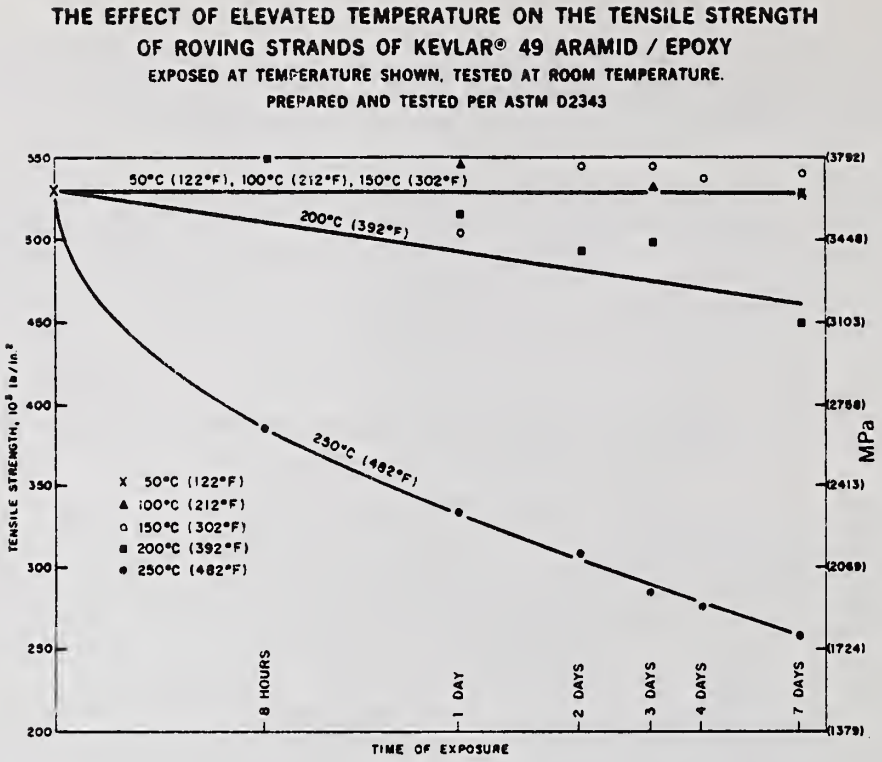


Figure 3

The major difference between Kevlar® and Kevlar® 29 versus Kevlar® 49 is modulus. (12MM vs. 18 MM PSI/IN^2).

The aerospace industry with its sensitivity to weight was one of the first to recognize the merits of the specific tensile strength of Kevlar®. Pictured is the Trident Missile. All three stages of this missile are filament wound composites motor cases of Kevlar®. Engineers were able to effect about 800 lbs. of weight savings replacing S glass with Kevlar®.

Pictured is the filament wound motor cases that are used in the Trident Missiles. This same configuration and missile casement construction will be used for the new MX Missile. (Fig. 4).

Figure 4

Shown is the middle stage of the Trident. (Fig. 5).

Pershing missile shown has two motor cases reinforced with Kevlar®. (Fig. 6).

Figure 5

Figure 6

Coming from the missile development are pressure bottles reinforced with Kevlar® 40. Pictured are two round cylinders that came from the space lab and a cylindrical bottle which is used on the Boeing 747 for inflating their escape slides. The round bottles are being evaluated for possible use as pressure water bottles and waste containing bottles on commercial aircraft. (Fig. 7)

Figure 7

In aircraft and helicopter the key programs are the:

Boeing 767
DeHavilland's Dash-7
Lockheed's L-1011
Sikorsky "Sprit S-76"

Aircraft manufacturers are making significant use of Kevlar® both on the exterior and interior of aircraft to reduce weight. Increase in fuel prices since the OPEC oil crunch has resulted in fuel price increases from $0.13 in the early

1970's to over $1.10 today. This has resulted in the fuel cost rising from 18% of direct operating cost to approximately 55% of DOC on commercial jet carriers. An estimated fuel cost to fly one pound of weight on a commercial aircraft for a year is $360.

Lockheed engineered use of 2,500 lb. composites of Kevlar® on their L-1011-500 in the early 1970's, resulting in a weight savings of over 800 lbs. NASA evaluations seven years later are showing these parts to be performing satisfactorily.

Recent committal to composites by Boeing containing Kevlar® for the 767 has resulted in 1,000 lbs. of weight savings.

The de Havilland Aircraft Co. were able to save 200 lbs. of weight by using Kevlar® to replace fiberglass on their DASH-7, a much smaller commuter aircraft.

The use of light weight, aramid fiber reinforced plastics in the 50-passenger DASH-7 is extensive, including the complete cabin interior and floors of Kevlar® 49 epoxy/Nomex® honeycomb sandwich construction. Externally, Kevlar® is used in the nose avionics compartment, the leading edge of the flaps and various aerodynamic fairings, many with complex double curvatures.

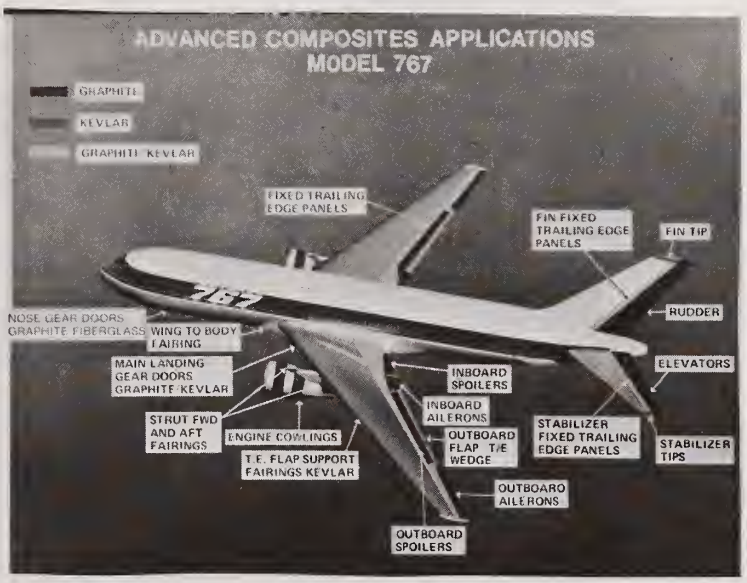


Figure 8

Over 50% of the exposed surface of the S-76 consists of advance composites reinforced with Kevlar® 49, representing in total, 138 internal and 25 external components, for a weight saving of 30% versus conventional structures.

Kevlar® has found a wide range of use in the interior and exterior use of commercial aircraft. In the interior, Kevlar® is basically used for all the fiber reinforced plastics.

Shown is the interior of the Concord produced by British Aerospace, where Kevlar® was used extensively in the sidewalls, overhead storage and ceiling panels, bulkheads, etc. (Fig. 9)

Figure 9

The first radar dome reinforced with Kevlar® was on the Cessna Citation I. The Citation 3, now in production, uses Kevlar® in the various fairings plus motor nacelles in addition to the radar dome.

The passenger seat for Cessna's 402 passenger aircraft is reinforced with Kevlar®. This seat weighs 13 1/2 lbs. versus the lightest weight metal tube seat which weighed 32 lbs. (Fig. 10)

Figure 10

In aircraft motor nacelles, Kevlar® is experiencing fast growth.

Shown is a Rohr Industry motor nacelle made with Kevlar® for the Boeing 727. The weight saved on this nacelle is between 40 & 45% lighter than the metal it is replacing. (Fig. 11)

Figure 11

Pictured is the Douglas DC-9-80 motor nacelle of Kevlar®, opened. (Fig. 12)

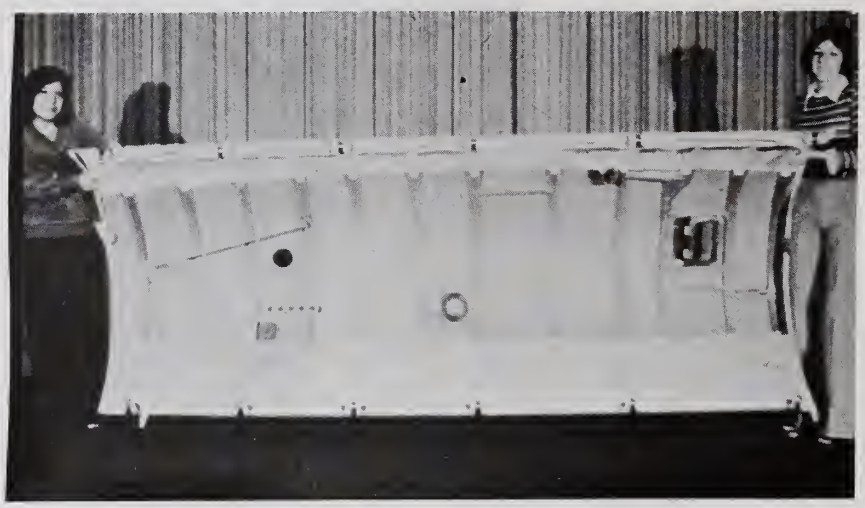


Figure 12

Helicopters are very weight sensitive because of the way the weight has to be lifted. For this reason, a pound of weight saved on a helicopter probably has the highest value of any of the aircraft. In one particular contract, the supplier is paying $800 per pound for weight saved. Normally, we estimate a lb. of weight saved on a helicopter being worth around $300/lb.

The Black Hawk helicopter is being produced by Sikorsky for the U.S. Army. Kevlar® is used in various fairings and doors on this helicopter; the dog house or the area around the engine is a typical application.

After the development of the Black Hawk, Sikorsky used their technology to develop the S-76 commercial helicopter. This is a 10-passenger helicopter. Here Kevlar® was used to save 30% in the frame weight. (Fig. 13)

Figure 13

Boeing are developing a commercial Chinook helicopter for servicing the North Sea oil platforms. This helicopter will probably be constructed with more pounds of advanced composites than any helicopter flying. They use Kevlar® and Nomex® honeycomb in the fuel cells on both sides of the aircraft. These fuel cells are supported by a beam made of Kevlar® with graphite caps. The floor of the helicopter is made from tapes of Kevlar® and supported with beams of Kevlar®. The motor cowlings and front section of the helicopter are slated to be Kevlar® solid laminates. (Fig. 14)

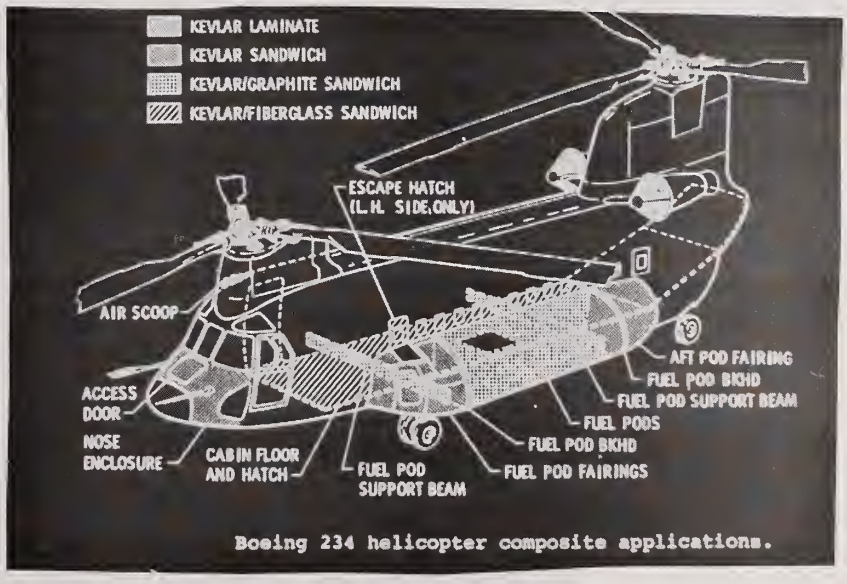
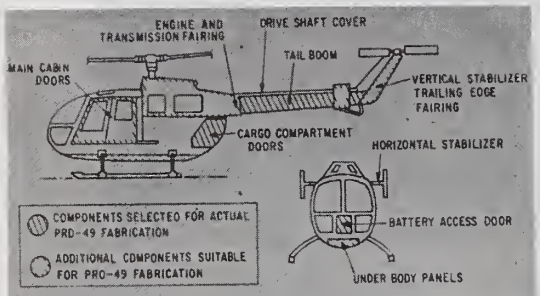


Figure 14

This is a summary of Boeing's & MBB's evaluation of possible use of Kevlar® for replacement of fiberglass and aluminum on their BOE-105 helicopter. This study was made about 5 years ago and use of Kevlar® has been implemented. They have been able to save more than the 11% weight first estimated. MBB have a contract for over 400 of these helicopters for the German army. (Fig. 15)

Shown is a Hughes AAH-64A, close ground support army helicopter. Much more Kevlar® has now been adopted for this helicopter than shown. (Fig. 16)



COMPONENTS CONSIDERED FOR FABRICATION IN PRD-49	PERCENTAGE REDUCTION (%)
COMPONENTS CURRENTLY FABRICATED FROM S-GLASS COMPOSITE	
FUSELAGE UNDERBODY PANELS	20
REAR CARGO COMPARTMENT DOORS	40
ENGINE AND TRANSMISSION FAIRING	20
CABIN DOORS	20
BATTERY ACCESS DOOR	55
VERTICAL STABILIZER TRAILING EDGE FAIRING	20
COMPONENTS CURRENTLY FABRICATED FROM ALUMINUM ALLOY	
FLOOR PANELS (MAG AND ALUMINUM)	42
TAIL ROTOR DRIVE SHAFT COVER	48
TAIL BOOM	22
HORIZONTAL STABILIZER AND END PLATES	20
CABIN ROOF AND SIDE STRUCTURE	47

Figure 15

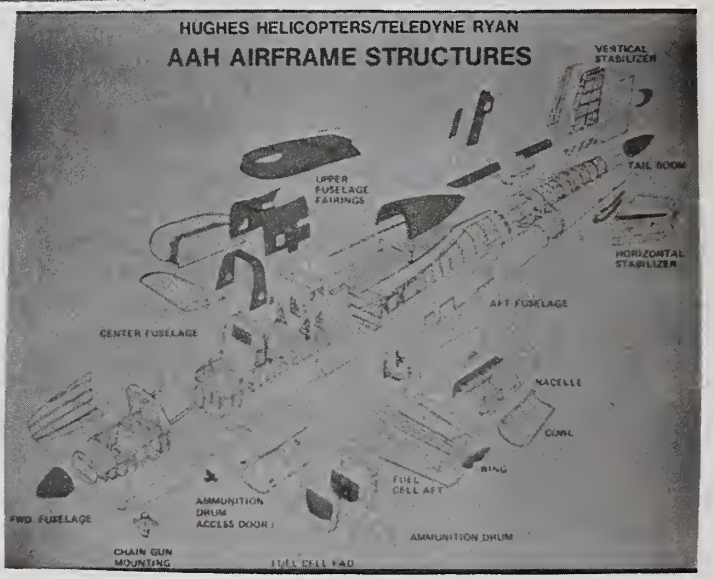


Figure 16

This is a prototype rotor blade for the AAH 64 helicopter, by Hughes, that is made using Kevlar® fiber for reinforcement. It is a good bit lighter than a similar one of fiberglass. This blade is presently going through in-flight evaluation. (Fig. 17)

Bell Helicopter are putting on 40 existing Bell-206 helicopters, 3 major parts for NASA durability evaluation. (Fig. 18)

Figure 17

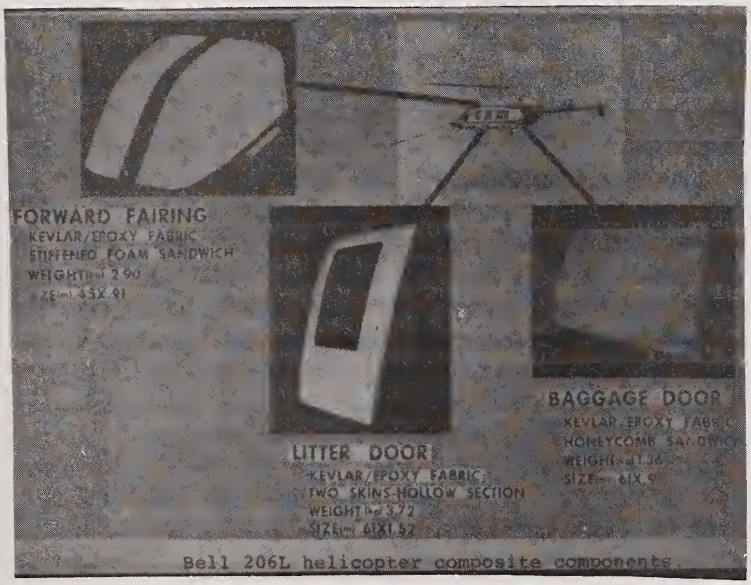


Figure 18

Applebay produced the first sailplane with its laminates predominately reinforced with Kevlar®. The Zuni II is ~70 lbs. lighter than the same sailplane in fiberglass.

Kevlar® is being developed for escape slides for commercial aircraft. Its potential advantages are weight savings plus improved resistance to radiant heat. It does not stretch when it is inflated, making it easy to put back into the pack. (Fig. 19)

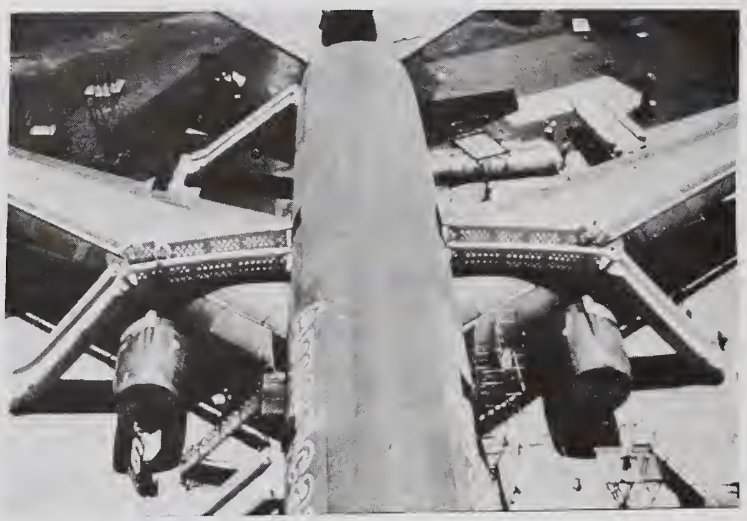


Figure 19

Pictured is a cargo container of Kevlar® 49 developed for Pan Am. Kevlar® offers a 10-20% weight reduction and hopefully a big increase in damage tolerance. We presently have 22 of these containers flying around the world. The containers are marked so that if any damage occurs, they call in the damage to Central Control. To date, we have had no reports of damage after 18 months. (Fig. 20)

In addition to the motor cowling use of Kevlar®, we feel that Kevlar®, in felt form, can help reduce noise. Also, the containment rings, which are presently titanium, can be replaced with fabrics of Kevlar®, offering 30-50% weight savings. The major engine manufacturers presently have Kevlar® under evaluation for containment rings.

Figure 20

There are various and sundry applications in space where Kevlar® is being used. It has been used for structural parts for the satellite and antennas that are being used by many broadcasting companies. We see the future for Kevlar® being widely used in aerospace applications.

We have various studies and articles that are available to you to help in any evaluation of Kevlar® you may be contemplating. Please let us know how we can help you!

SESSION V

INNOVATIVE MAINTENANCE DIAGNOSTICS AND MAINTENANCE INDICATORS

CHAIRMAN: M. B. PETERSON
WEAR SCIENCES, INC.

THE ROLE OF NEUTRON RADIOGRAPHY IN A MAINTENANCE ENVIRONMENT

Joseph John
IRT Corporation
P.O. Box 80817
San Diego, CA 92138

ABSTRACT

Neutron radiography is similar to x-ray inspection in that both depend upon use of radiation that penetrates some materials and is absorbed by others to provide a contrast image of conditions not readily available for visual inspection. But an important difference is the type of materials that absorb each of the two kinds of radiation. X-rays are absorbed by dense materials, such as metals, whereas neutrons readily penetrate metals but are absorbed by materials containing hydrogen.

The neutron radiography technique has been successfully applied to a number of inspection situations. These include the inspection of explosives, advanced composites, adhesively bonded structures and a number of aircraft engine components. With the availability of Californium-252, it has become feasible to construct mobile neutron radiography systems suitable for field use. Such systems have been used for in situ inspection of flight line aircraft, particularly to locate and measure hidden corrosion.

Key words: Composite inspection; corrosion detection; cost savings; NDE; neutron radiography; preventive maintenance.

1. INTRODUCTION

Neutron radiography is a nondestructive inspection technique that is similar in principle to x-ray, in that a penetrating radiation (neutrons) is used to obtain a visual image of the internal form of an object. The transmitted neutron beam is detected and permanently recorded on a suitable imaging system (usually film). The recorded image represents a shadow of the object with the lower density on the image corresponding to portions of the object that are more effective in attenuating the direct neutron beam.

Although neutron radiographic and x-ray techniques are similar in principle, they actually complement each other. This is because the relative absorption characteristics of most elements are essentially reversed; thermal neutrons are highly attenuated by light elements. Thus with neutron radiography, nondestructive inspection can be made of light elements or certain defects encased in or behind heavy elements. It can detect imperfections in thick samples through which x-rays cannot penetrate, or in samples containing hydrogeneous matter or contaminants whose neutron absorbing and scattering properties differ significantly from the base material.

The mass absorption coefficients of naturally occurring elements for neutrons and x-rays are displayed in Figure 1. When plotted as a function of atomic number, the mass absorption coefficient for x-rays is a smoothly varying function increasing with atomic number. On the other hand, the corresponding values for neutrons fluctuate from element to element, and on the average decrease with increasing atomic number. Hence, in general, the lightest elements (particularly hydrogen) are the most opaque and the heavier elements are the least opaque to thermal nuetrons. This characteristic is the opposite of the attenuation properties of x-rays in which the heavy elements, such as lead, are the most opaque and the light elements are quite transparent. Hence, by complementing x-ray inspection the neutron radiographic technique extends the capability of radiography to a much broader spectrum of applications.

The majority of neutron radiography is performed with neutrons having an energy of 0.3 eV or less. The neutrons are in thermal equilibrium with the surrounding material so that there is no net transfer of kinetic energy between the neutrons and the surrounding medium. The average energy of thermal neutrons is usually taken to be 0.025 eV. Thermal neutrons are more widely used because of their higher probability of interaction with most materials. This makes them easier to detect and gives the best contrast between the elements of interest and the surrounding medium.

In the past, the availability of suitable neutron sources has limited the growth and application of neutron radiography. Nuclear reactors and large accelerators which are commonly used are expensive to acquire, troublesome to maintain, and lack portability. However, the availability of the man-made isotope Californium-252, a copious emitter of neutrons, and small accelerators has made it feasible to construct neutron radiographic systems, which because of their lower cost and portability, promise to significantly expand the use of neutron radiography for nondestructive inpsection.

2. IMAGE SYSTEMS FOR NEUTRON RADIOGRAPHY

The purpose of the system is to photographically detect neutrons. Unlike x-rays, neutrons do not interact with normal photographic films; therefore, a converter screen must be used with a conventional x-ray film to produce a permanent image. The role of the converter screen is to change the neutron image to alpha, beta, or gamma radiation which is detectable by a wide range of x-ray films.

Two different methods of exposure may be utilized in neutron radiography, depending on the type of converter used. Some of the metal converters and all of the scintillators emit their radiation promptly upon capturing a neutron. These converters are used in the direct-exposure method, with the converter screen and film exposed to the neutron beam together. The transfer method exposes only the converter screen to the neutron beam. Upon capturing the neutron, the metal screen becomes radioactive and emits a delayed radiation in a time period that is characteristic of the specific isotope produced in the metal screen. The delayed radiation is used to activate the film. The transfer method is useful when the object is radioactive, the neutron beam is contaminated with gamma rays, or the very best contrast is desirable.

Converters fall into two general classes: metal screens that emit low-energy gammas or x-rays often accompanied with electrons, and scintillators that are loaded with ^{6}Li or ^{10}B that captures the neutron and emits an alpha particle, which in turn excites the scintillator material (ZnS) into emitting visible light. As one would expect, metal converters use standard x-ray film and scintillators use light-sensitive film.

The most common converter screen used in neutron radiography is gadolinium. Gadolinium screens can only be used in the direct-exposure method as it emits soft gamma rays and 70-keV electrons promptly upon capturing neutrons. Using a thin Gd converter about 0.001-inch-thick, very high-resolution radiographs are possible. Resolutions of less than 0.0005 inch have been achieved using Gd converters in neutron beams having low angular divergence.

X-ray films having a range of speeds from 100 to 1600 (GAF Ref) are routinely used with the converter screens mentioned above. Resolution of cracks or opaque inclusions with one-mil dimensions are possible with GAF 100 or EK SR film when good radiation geometry is present.

Combinations of scintillator material and photographic film have been produced to obtain increased speed by Gavaert, Polaroid, and 3M Company. Resolution suffers, but some interesting applications are possible.

As more sensitive imaging systems become available, fewer total neutrons are required to produce the desired image. However, a quantum limit exists that is determined by the statistical accuracy necessary to define an object over a given

area. This limit is approximately 10^6 n/cm^2. Fewer neutrons than this per unit area will produce a fuzzy image no matter how sensitive the converter screen.

Other imaging techniques have been tried or are being developed. The track-etch method uses cellulose nitrate screens to detect hydrogen atoms that have been scattered by the neutron beam. Neutron television systems are being studied using a scintillator material. Multiwire spark counters, similar to those used in high-energy particle experiments, are also being developed for neutron radiography.

3. NEUTRON RADIOGRAPHY CAMERA

The basic function of a neutron radiographic camera is to achieve as large a thermal neutron flux as possible at the object and imaging system with a minimum of gamma rays. In addition, the thermal neutron flux must arrive at the imaging plane in a beam to produce a sharp, clear picture of the object.

^{252}Cf is a compromise on the ideal neutron source for neutron radiography. It is true that ^{252}Cf has several of the attributes of an ideal source. It is a very intense source (essentially a point source) with relatively few gamma rays. Unfortunately, the neutron energy distribution is similar to a fission spectrum with an average neutron energy of slightly over 2 MeV. Consequently, to do thermal neutron radiography, it is necessary to reduce the average energy of the neutron spectrum. The moderation of the neutron energy distribution is accomplished by placing the ^{252}Cf source in a material that has a high density of hydrogen. Hydrogen has the unique ability of moderating the neutron energy in the fewest number of scattering collisions and thus in the smallest volume.

Now that we are forced to use a neutron source with a finite volume to generate thermal neutrons, we must define an aperture through which the neutron beam must go to get to the imaging plane. To do this effectively, a hole is introduced into the moderator region that extends into the middle of the material next to the source. This is the region with the highest thermal-neutron flux density.

The aperture looks at the imaging plane through a divergent collimator. The collimator is made divergent to maximize the neutron flux over as wide an area as possible. The function of the collimator is to capture (with a minimum of gamma activity) all neutrons that might possibly scatter into the imaging plane.

The image plane is the location of the object. The film must be placed as close as possible to the object to produce clear, high-resolution radiographs. The geometric unsharpness of a radiograph is inversely proportional to the L/D ratio, where L is the distance from the aperture of dimension D to the imaging plane. It is usually convenient to have a variable L/D ratio by allowing for a variable L and/or D.

The bulk of a neutron camera consists of biological shielding. The cheapest shielding material for a neutron source is water. Unfortunately, water can be inconvenient in that it has a tendency to leak and provides poor gamma-ray shielding. We use a solid material that contains a large amount of water and can also be mixed with other neutron capturing material to reduce the amount of secondary gamma rays that are produced. This material is called water-extended polyester (WEP). It is an efficient neutron and gamma shield when mixed with material containing boron.

In principle, a neutron camera with proper shielding can be operated in the same room with personnel. However, for safety reasons, it is best to have controlled access to the camera area. A shutter and interlock system can be provided that essentially eliminates the remotest possibility of a radiation accident. The access door and the shutter automatically closes. Loss of power will also cause the shutter to close. Additional safety features include a flashing light when the shutter is open, a radiation monitor with a threshold setting, a shut-off from the cells, and a console key lock.

3.1 PORTABLE NEUTRON-RADIOGRAPHY SYSTEM

A standard neutron-radiography system using ^{252}Cf weighs far too much to enable its use as a convenient portable source to inspect an aircraft or an aircraft component without first removing it from the aircraft. Fortunately, most of the weight resides in the biological neutron and gamma-ray shielding necessary if personnel are to be in close proximity to the radiography system. The camera itself consists only of the source, moderator, and thermal-neutron collimator, and weighs approximately one tenth of a standard fixed system. Hence, a portable system, consisting essentially of only the camera components, has been shown to be feasible [1] if the need for personnel to be in close proximity during exposure is eliminated.

Such a portable camera, improvised for aircraft maintenance inspection, is shown in Figure 2. This system is shown readied to inspect the wing tank of an E-2 aircraft [2]. Although this system has not been specifically designed for mobile operation, its performance in this less-than-optimum configuration helps to demonstrate the feasibility of a portable neutron-radiography system (see Ref 3 for additional discussion). The camera and the biological shield are constructed as separate entities, with the source residing in the shield except during actual exposure. The portable neutron-radiographic camera is located on top of the aircraft wing, with the beam aimed downward. The cylindrical biological shield is located on the right-hand portion of this figure. The two subsystems are connected by a polyethylene hose through which the source is transferred between the camera and the shield by a flexible cable.

The process of making an individual exposure consists of positioning the film cassettes on the lower surface of the wing under the camera. The exposure is initiated by transferring the ^{252}Cf source from the storage container by means of a crank-driven cable. The cable arrangement allows the operator to stand some 25 feet away from the camera during source transfer, as shown in Figure 2.

When the crank is driven forward, the flexible cable with a magnetic tip moves from the neutron camera through the polyethylene hose, which guides the cable into the source storage container. The magnetic tip of the cable is driven down against the source, and with contact a magnetic latch is established. The crank mechanism is then reversed, withdrawing the cable, with the source magnetically attached, from the storage container back through the polyetheylene tube into the camera body. This operation requires about four seconds. The exposure is terminated by reversing this process, thereby transferring the source from the camera into the source container.

Using 5.8 mg of ^{252}Cf, it was possible to inspect 6-1/2 square feet of the lower skin of the E-2 aircraft integral fuel tank in a single exposure, lasting approximately 2-1/4 hours. The radiographic geometry allowed the resolution of most spherical clusters of corrosion with a diameter of 0.010 inch, which was considered adequate.

To comply with radiation safety regulations, an exclusion area having a radius of approximately 140 feet is necessary. The total radiation dose at the perimeter of this area if 2 mrem/hr during exposure. When necessary, partial radiation shields consisting of borated paraffin positioned between the camera and maintenance personnel can reduce the exclusion area to permit access to other portions of the aircraft during an exposure.

A series of programs (4 - 12) have been carried out to evaluate applications of neutron radiography to solve a number of inspection problems. A selected set of examples are described in the following section.

4. SELECTED APPLICATIONS

4.1 METAL JACKETED EXPLOSIVES

Neutron radiography is quite effective for inspecting metal-jacketed explosive devices to observe density variations, voids, and foreign materials. This application provides excellent examples of the ability of neutrons to effectively image light materials within heavy ones. Examination of the same components with x-rays only reveals the metallic claddings. Aircraft depend on propellant-activated devices and linear-shaped charges for emergency escape systems; here fast and reliable performance is demanded. Figure 3 shows three neutron radiographs taken with varying L/D ratios of small explosive train devices with known defects, such as missing end tips. These pictures establish that although radiographs wth an L/D of 140 obtain the best resolution, an L/D of 11 provided radiographs with adequate resolution to discern many defects. This reduction of L/D from 140 to 11 is accompanied by a reduction in the exposure time by a factor of about 100.

Figure 4 shows three shielded mild detonating cords with known gaps of 2, 5, and 12 mils; these cords are sealed in stainless-steel cases. Neutron radiographs taken with the ^{252}Cf camera successfully detected all of these gaps. Here again, it should be noted that x-ray inspection images only the stainless-steel casings and provides no information on defects in the explosive.

A number of pyrotechnic devices are used in the F-111 aircraft system. These are widely used in emergency escape mechanisms. One such device, consisting of the end fittings and a line charge enclosed in a metallic sheath, is shown in Figure 5; this is a photograph of the device. The radiograph shown in Figure 6 clearly images the explosive charge, since the metallic sheath is transparent to neutrons. In this particular case, the pyrotechnic device is in good condition and is devoid of any defects.

4.2 ADVANCED COMPOSITE MATERIALS

The development and widespread use of advanced composites in aircraft structures calls for a parallel effort in the development of new NDI techniques for inspecting these components. Conventional NDI techniques, developed primarily for metallic components, will become of limited use as components fabricated from these advanced composites begin to replace the all-metal ones. Neutron radiography is capable of inspecting these composites, an example of which is shown in Figure 7. This is a single layer of tungsten-boron fibers in an aluminum matrix. The filaments consist of 0.5-mil tungsten core coated with boron to make 4-mil fibers. This neutron radiograph is able to see single filaments for detailed inspection. Cracks and other defects are easily observed.

4.3 INSPECTION OF ADHESIVE BONDED STRUCTURE

Neutron radiography is quite effective in detecting common defects in adhesive bonded honeycomb structure. Since neutron radiography highlights the organic adhesive material instead of the metallic core seen by x-rays, it is possible to detect variations in adhesive density which can lead to inadequate bonding. This is illustrated in Figure 8. Shown here is a neutron radiograph of a test panel approximately 12 inches long, 7 inches wide, and 5/8-inch thick. The end panels are approximately 1/16 inch thick. The honeycomb structure visible in this radiograph shows the distribution of the organic adhesive around the metallic honeycomb core. This radiograph clearly shows four circular areas where no adhesive was applied to one of the end panels. Careful examination reveals that the edges of two of these circles are better defined than those of the other two, implying that two of these voids are on one side of the panel, while the other pair is on the opposite side. Since neutron radiography images the adhesive, rather than the metallic core, it is speculated that a technique involving neutron radiography may be possible to detect defective bonds resulting from the failure of the adhesive to wet the honeycomb.

A second example for inspecting adhesive bonded aircraft structure is seen in the case of the F-111 aircraft. The vertical stabilizer of the F-111 aircraft consists of phenolic honeycomb bonded to aluminum skin. The leading edge of the vertical stabilizer is an aluminum strip shaped in the form of an arrowhead. The adhesive bond lines between the aluminum arrowhead and the aluminum skin have been suspected of being deficient, leading to the existence of minute leakage path ("worm holes") connecting the honeycomb cells to the outside environment. It is surmised that water accumulation in the honeycomb cells results from these leakage paths. During supersonic flights, considerable heat is produced in the region of the leading edge, causing the water to boil and resulting in the rupture of the skin and loss of portions of the vertical stabilizer in flight.

A neutron radiographic examination of an F-111 sample was performed and the resulting radiograph is displayed in Figure 9. This radiograph clearly shows the adhesive bond line between the arrowhead and the aluminum skin. A careful examination of the radiograph reveals adhesive deficiencies, and a number of possible paths linking the honeycomb cells to the outside environment can be identified. In addition, this radiograph reveals great nonuniformity in the application of the adhesive in this region.

Several models of helicopters are equipped with main rotor blade systems that are bonded by adhesives. Failures of these bondings have been attributed to insufficient amounts of adhesive in the bond area, voids or air bubbles in the adhesive, improper preparation of the bond surface, corrosion of the surfaces under the adhesives, or a variety of other possible causes. Such defects are known to result in catastrophic failures, particularly when the disbonding occurs in the closure of a C-shaped spar of the main rotor blade system.

The feasibility of using the neutron radiographic technique to detect these disbonds has been established through a program [8] conducted at IRT Corporation. Selected test blades were subjected to the standard neutron radiography procedure. The neutron beam from the camera was directed toward the sample at an angle so that the adhesive region on one side of the C-spar, between the spar and the spar closure, was clearly imaged on the film. The orientation of the blade was such that the adhesive region on the opposite side of the C-spar did not interfere with imaging of the adhesive bond close to the film. These radiographs showed areas of nonuniform adhesive distribution, but were naturally unable to detect disbonded areas that were properly bonded prior to use.

A suitable enhacing agent was then used to wet the area near the spar closure. The orientation of the blade was such as to encourage the penetrant to seep into areas where any disbonding occurs. After a short period of time the excess penetrant was removed, and the sample was subjected to a second inspection. The penetrant, a good absorber of neutrons, helped highlight the disbonded or unbonded area.

Figure 10 shows a composite of two neutron radiographs obtained with a blade. At the top is a standard radiograph clearly showing the honeycomb structure in the trailing portion of the blade. The bond line is the region between the two parallel lines below the honeycomb. The lower radiograph was taken after treatment with the penetrant. The disbonded portion of the spar closure area allows the penetrant to enter the space between the spar and the closure tip, highlighting the area of disbond. The extent of disbond is clearly identified.

A second type of defect in helicopter blade detected by neutron radiography is illustrated in Figure 11. The bond line, in this case, appears uneven and discontinuous, indicating the location where fretting corrosion has occurred. When two metal surfaces are allowed to rub against each other due to insufficient amount of adhesive, fretting often results which leads to the initation of cracks followed by catastrophic failure.

After completion of the neutron radiographic inspection, these blades were disassembled and subjected to visual inspection. The disbonds detected by this destructive inspection process correlated exactly with the defects identified by neutron radiography.

4.4 INSPECTION OF AIRCRAFT ENGINE COMPONENTS

Turbine engine blades and vanes for high-temperature applications are generally cooled by internal passages formed by investment casting processes. Air is supplied at the base of the blade, which flows through the passageways cooling the blade and exits through a series of holes. Cooling is aided by the use of pins and fins within the blade, which increase the surface area to improve the heat transfer efficiency.

A ceramic core is used to form the cooling passages when the blade is cast, and after casting this core is chemically leached out. The high operating temperatures necessary to achieve higher engine efficiency demand that all the ceramic core be removed. Any amount of residual core remaining in the blade can cause the cooling passages to be blocked, which will reduce durability and can lead to blade failure. The amount of residual core remaining which could cause serious damage is below the resolution limits of x-radiography.

Figure 12 shows an x-radiograph of a set of TF-41 turbine blades on the left and the corresponding neutron radiograph on the right. The x-radiograph is able to detect the large amount of residual core which is blocking almost the entire cooling passage. This residual core is seen with much greater contrast in the neutron radiograph. As the amount of core is reduced, x-radiography is unable to detect it, but it is still clearly imaged in the corresponding neutron radiograph.

Turbine blades, fuel manifolds, and oil lines in aircraft engines are often clogged by coke deposits. The high temperatures at which these components operate cause the hydrocarbons in the fuel and oil to dissociate depositing carbon on

their surfaces. Figure 13 is a composite of three neutron radiographs showing sections of oil lines of a CF-6 aircraft engine. Coke deposits are visible on the inner surfaces of these tubes. A large piece of coke, dislodged from the tube wall, is seen resting near the shoulder of the 'J'-shaped tube.

The TF-30 engine used on high-performance military aircraft has been known to fail due to fatigue cracking of compressor and turbine blades. An example is shown in Figure 14 which contains a neutron radiograph of the tip of a compressor blade. The cracks are clearly imaged in the radiograph. The enhancing used in this case assists in defining the orientation of the cracks [14].

4.5 DETECTION OF CORROSION IN AIRCRAFT STRUCTURE

Corrosion within the cross sections of aircraft structures can affect the structural integrity, resulting in damages that range from fuel leakage to catastrophic failures. The timely detection of corrosion is essential if corrective measures are to be taken to arrest corrosion and avoid subsequent expensive rework.

The primary technique at present for identifying corrosion is visual detection of external manifestations of corrosion, such as appearance of blisters or the swelling of skin blanket. This technique completely fails when the corrosion is at the interface between two structural members, or is concealed behind a heavy coating of sealant.

4.5.1 Wing Tank Corrosion

The wing fuel tanks of aircraft have been known to be susceptible to in-service corrosion and subsequent damage. This has been attributed to moisture seepage under the sealant and between the skin and ribs, spar flanges, and fasteners. Corrosion damage identified by de-skinning, or cutting out skin portions so corroded that fuel leaked through, has not shown a pattern related to either flight hours or months in service. Visual inspection through available access panels covers only a small fraction of the area, making the identification of wings requiring priority rework and definition of safe damage limits unreliable.

The extreme effectiveness of the neutron radiographic technique to identify corrosion is illustrated by two examples in the following subsections.

4.5.1.1 Wing Tank Corrosion in a Commercial DC-9 Aircraft.

Several instances of exfoliation corrosion in the outboard flange of station Xcw = 58.500 lower tee cap in DC-9 aircraft have been reported. Exfoliation corrosion is attributed to fuel contamination or water or both, allowing corrosion to originate between the stringer and the tee cap. Exfoliation corrosion in the tee cap has been reported on aircraft having as few as 10,000 flight hours.

The recommended inspection procedure called for visual inspection, followed by the addition of a radio-opaque oil and subsequent x-ray inspection. The special oil mixture is forced into the area between the stringer and the tee cap using a vacuum method prior to x-ray inspection. The results obtained with x-rays are unsatisfactory. Since the stringer is nearly two inches thick, x-rays merely display the outline of the stringer and fail to reveal corrosion (see Figure 10 in Ref 4).

Under a program sponsored by Douglas Aircraft Company, a series of radiographs has been taken simulating in situ inspection of a DC-9 aircraft. A set of stringers, received from Douglas Aircraft Company, was inspected using the portable neutron-radiography system, and the resulting neutron radiograph is shown in Figure 15. It displays the outline of the thick portion of the stringer, the tee cap, and the bolts attaching the stringer to the tee cap. In addition, the radiograph clearly reveals the extent of corrosion through the thick stringer, and presents no difficulty in interpreting the results. A composite photograph showing two views of the tee cap surface is given in Figure 16. Tee caps marked 13 and 14 correspond to the radiograph displayed in Figure 15. It is clear that the surface has been subjected to a major corrosion attack. It should be noted that Figure 16 displays only the corrosion visible on the surface, whereas the radiograph in Figure 15 images both surface and subsurface corrosion, and hence the apparent disparity in the extent of corrosion seen in these two figures.

The main factor in favor of the neutron radiographic technique is that it does not require visual inspection, the application of radio-opaque oil, or intrusion of the oil into a corroded area for detection. Also, it does not require removal of the barrel nut or evacuation of the barrel nut hole. It could also locate corrosion between the wing skin and the tee cap if it exists.

4.5.1.2 Corrosion in C-130 Aircraft Wing

The C-130 Hercules aircraft has all-metal wings, with two-spar stressed-skin structure, with integrally stiffened, tapered, machined skin panels. Several instances of extensive surface and intergranular corrosion have led to fuel leaks in this aircraft. This problem is particularly difficult to identify when the corrosion is located within the lap joint.

This wing-tank problem is illustrated in Figure 17. This is a photograph of a portion of the lower wing-tank structure of a C-130 aircraft. It clearly shows the origin of the corrosion attack. An inspection of the upper surface of the skin does not provide any indication of the severity of corrosion damage. Figure 18 shows two neutron radiographs of this sample. The radiograph on the right half of this figure is a standard neutron radiograph. It shows the corroded region to originate at the locations identified in Figure 17, and the intergranular corrosion to extend to one rivet hole. This could clearly cause a fuel leak, although the rivet itself may appear to be in good condition. When a small quantity of enhancing fluid is used, the corrosion feature is considerably enhanced, as shown in the neutron radiograph on the left half of Figure 18. This radiograph indicates

that the intergranular corrosion has enveloped several rivet holes, clearly explaining the cause of the fuel leak.

4.5.1.3 Stress Corrosion in A-7 Nose Landing Gear.

In the course of a program [6] sponsored by the Navy, a number of A-7 nose landing gear struts were screened using the neutron radiographic technique. This investigation was carried out to detect corrosion on the inner surface of the trunnion, at the interface between the aluminum housing and the bronze bushing. Disassembly of the gear for this inspection without damaging the component is very difficult. Over 52 landing gears were inspected, and nearly half of them were found to have been subjected to corrosion attack to some degree.

One of the most critical specimens examined during this study was an A-7 strut with a stress-corrosion defect. The defect appeared as a hairline crack in the trunnion region, barely detectable by visual inspection, even after the location was detected by an eddy current probe. However, the eddy current technique was unable to provide any additional information regarding the extent or shape of the stress-corrosion crack.

This strut was subjected to neutron radiographic inspection, and the resulting neutron radiograph is shown in Figure 19. The stress-corrosion crack is seen to originate at a point on the inner surface of the trunnion bore and extend almost to the outer surface, clearly showing the extent, shape, and nature of the crack. This appears to be the first experimental work in which a stress-corrosion crack has been imaged by neutron radiography.

The sample was then sectioned; a photograph of the sectioned trunnion area is shown in Figure 10. The extent of the stress-corrosion crack is clearly visible, and the correlation with neutron radiography is excellent.

4.5.1.4 Quantiative Determination of Corrosion

In order to take full advantage of this nondestructive inspection technique, it is desirable not only to identify the location of the corrosion, but also determine the extent of the corrosion damage. Hence, a program has been conducted to evaluate the potential of using the neutron radiographic technique as a quantitative tool to measure the depth of corrosion so that selective rework of the aircraft can be carried out. This work is reported in detail in References 9 and 13.

The results of the investigation show that an experimental relationship can be formulated which will quantitatively determine the corrosion depth from the film density measured from a neutron radiograph. This is graphically represented in Figure 21, showing the data obtained from a corroded torque-box panel of an F-4 aircraft. The deviation of the photographic density at a corroded point from the corresponding value at the undamaged portions (plotted along the ordinate) is shown to be proportional to the depth of corrosion (plotted along the

abscissa). Such linear relationships have been shown to exist for a variety of aluminum alloys used in the structure of aircraft that have operated in different environments.

This study has further established that the thickness of corrosion products and the thickness of aluminum remaining can be determined with a precision of two to three percent. This ability to precisely determine the amount of structural material remaining (particularly the aircraft skin in the case of integral fuel tanks) enables rework decisions to be based on actual structural conditions.

5. COMPARISON TO OTHER INSPECTION TECHNIQUES

In order to compare the corrosion detection capability of the neutron radiographic technique with those of other inspection techniques, a careful experiment was carried out on a flight-line aircraft. For this investigation, a particular E-2 aircraft was selected as a test vehicle due to its past history of in-service corrosion susceptibility. The lower skin of the wing tank was first surveyed with neutron radiography. The wing was later subjected to x-ray examination, ultrasonic scan, visual inspection after the upper skin of the wing tank was removed, and a second visual inspection after the sealant and paint was removed from the inner surface of the tank. The major conclusions of this study are:

1. The neutron radiographic technique, unlike x-ray and ultrasonic techniques, detects corrosion by the presence of corrosion products. Hence, this technique identified the actual condition of the skin, and therefore the interpretation requires no knowledge of its prior maintenance or rework history.

2. Neutron radiography permits inspection of 95 percent of the lower internal skin area. It can detect corrosion hidden under sealant, behind ribs, spars, spar flanges, and fasteners. On the other hand, x-ray, ultrasonic, and visual inspection techniques are severely restricted by the internal structure of the wing, as well as the uneven nature of the skin. Only 80 to 85 percent of the surface can be covered by a combination of these three conventional techniques.

3. Of the 419 regions of corrosion identified by neutron radiography, 284 were confirmed by ultrasonic inspection and a total of 309 were confirmed by a combination of all three conventional techniques. Most of the uncorrelated areas are accounted for by the limitations of the conventional techniques resulting from inaccessibility or from interfering structure. Only five discrepancies were attributable to poor interpretation of neutron radiographs.

6. COST EVALUATION

The E-2 aircraft inspection also provides a means of evaluating the cost savings to be achieved with neutron radiography. A complete inspection of the wing tank, as it is carried out now, calls for the deskinning of the upper wing surface, followed by the removal of the sealant and paint by chemical stripping or shell blasting. With the wing tank fully open from the top, visual access is now available to the entire exposed portion of the upper surface of the lower wing skin. However, even this elaborate and time-consuming operation does not provide a means of inspecting the region between the skin and ribs where corrosion is very likely to occur. Only complete disassembly of the wing structure can provide any sure way to conduct visual inspection of the entire wing tank for corrosion detection.

It is estimated that approximately 5,000 manhours are expended in reworking the integral fuel cell areas of a single E-2 aircraft for corrosion. This consists of deskinning, removal of paint and sealant, cleaning, visual inspection for corrosion, chemical conversion coating, application of new sealant, painting, reskinning, and checkout. The actual inspection portion of this procedure takes 428 manhours.

The experience gained with the E-2 aircraft shows that a team of two can carry out the neutron radiographic inspection, including setup, film developing, and interpretation. Allowing 16 manhours for initial preparation, and an equal amount for shutdown operations, the entire neutron radiographic inspection of the lower skin of the E-2 aircraft can be accomplished with an expenditure of 152 manhours. This is a substantial savings over the 428 manhours estimated to perform the inspection using the currently recommended practice. In addition, by eliminating the need for deskinning, paint removal, and reskinning required for visual inspection, it appears that the cost of acquiring and operating a neutron radiography system can be repaid in a short time, even if its use is restricted to the E-2 aircraft.

7. CONCLUSION

These studies have helped to establish that neutron radiography as a nondestructive inspection tool has a definite role to play in a number of inspection situations. Its capability complements those of other inspection techniques currently in use. The ability of neutron radiography to identify surface and intergranular corrosion, and to detect them quantitatively, is unique. The feasibility of performing neutron radiographic inspection in a maintenance environment is now clearly established.

8. ACKNOWLEDGMENTS

A large number of persons have contributed to making this program possible, and any attempt to name them would only result in an incomplete list. The author would like to acknowledge their assistance. Special mention should be made of the assistance received from Naval Air Systems Command, Air Force Logistics Command, and Army Aviation Systems Command.

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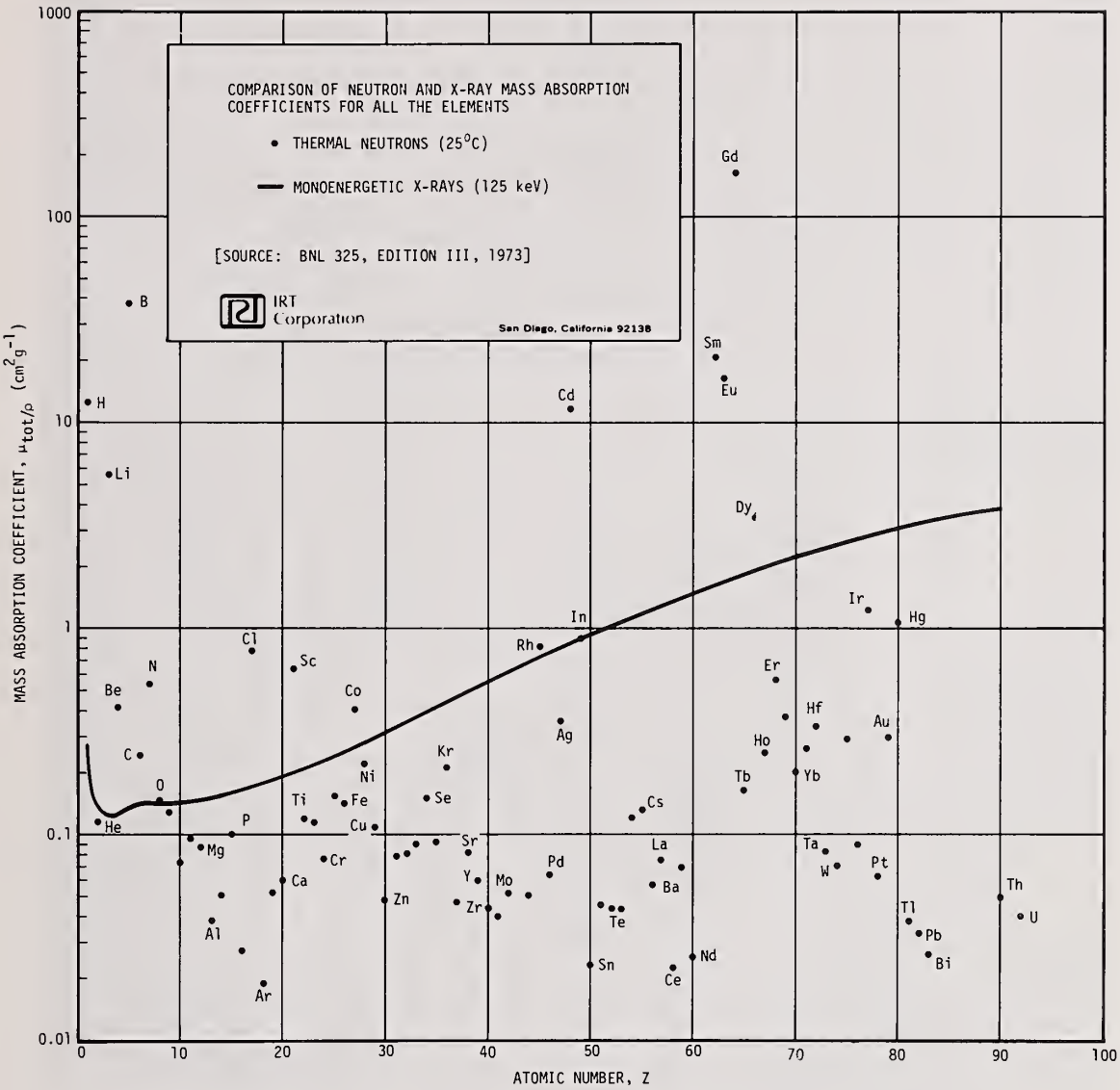

Figure 1. Comparison of x-ray and n-ray mass absorption coefficients

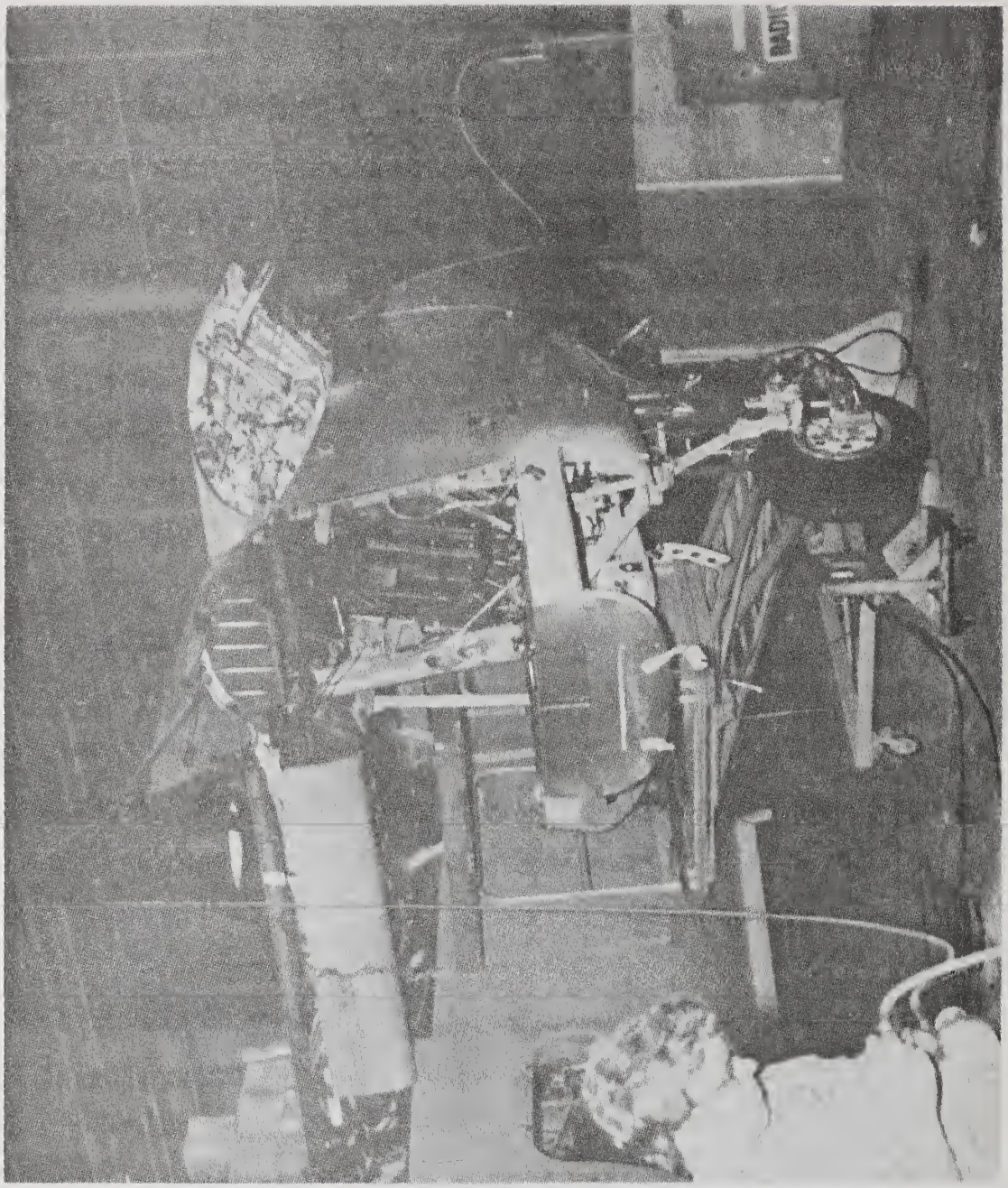

Figure 2. Portable neutron radiography camera positioned to radiograph lower skin of aircraft fuel tank. The camera is mounted on top of the wing, with the neutron beam aimed downward. The Californium-252 source normally resides in the biological shield shown on the right-hand side of the photograph. The operator initiates an exposure by moving the source from the cask into the camera through a flexible hose using a remotely operated cable-driven mechanism.

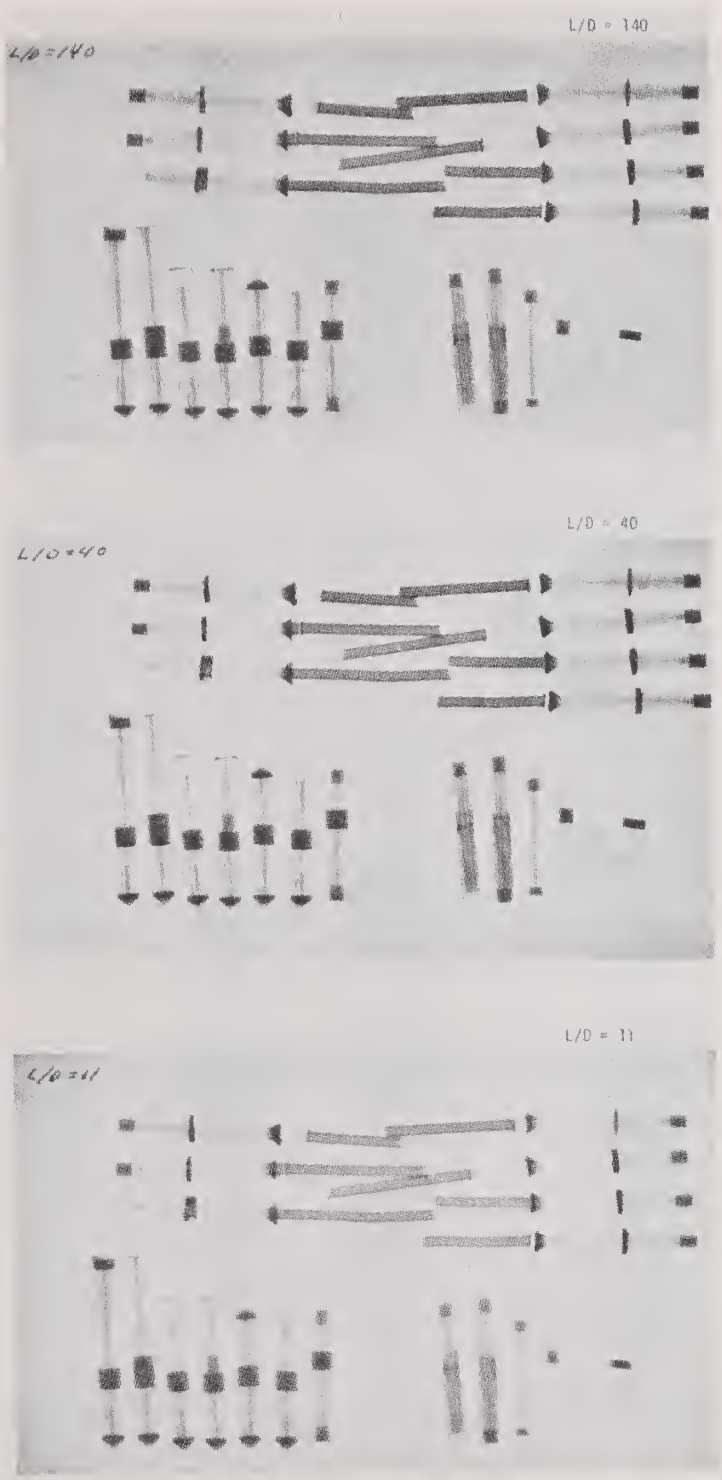

Figure 3. Prints of neutron radiographs of explosive train devices having known defects (such as missing end tips) taken with L/D ratio (resolution) of 140, typical of reactor-based radiography, and L/D ratios of 40 and 11, more typical of Cf-252-based neutron radiography.

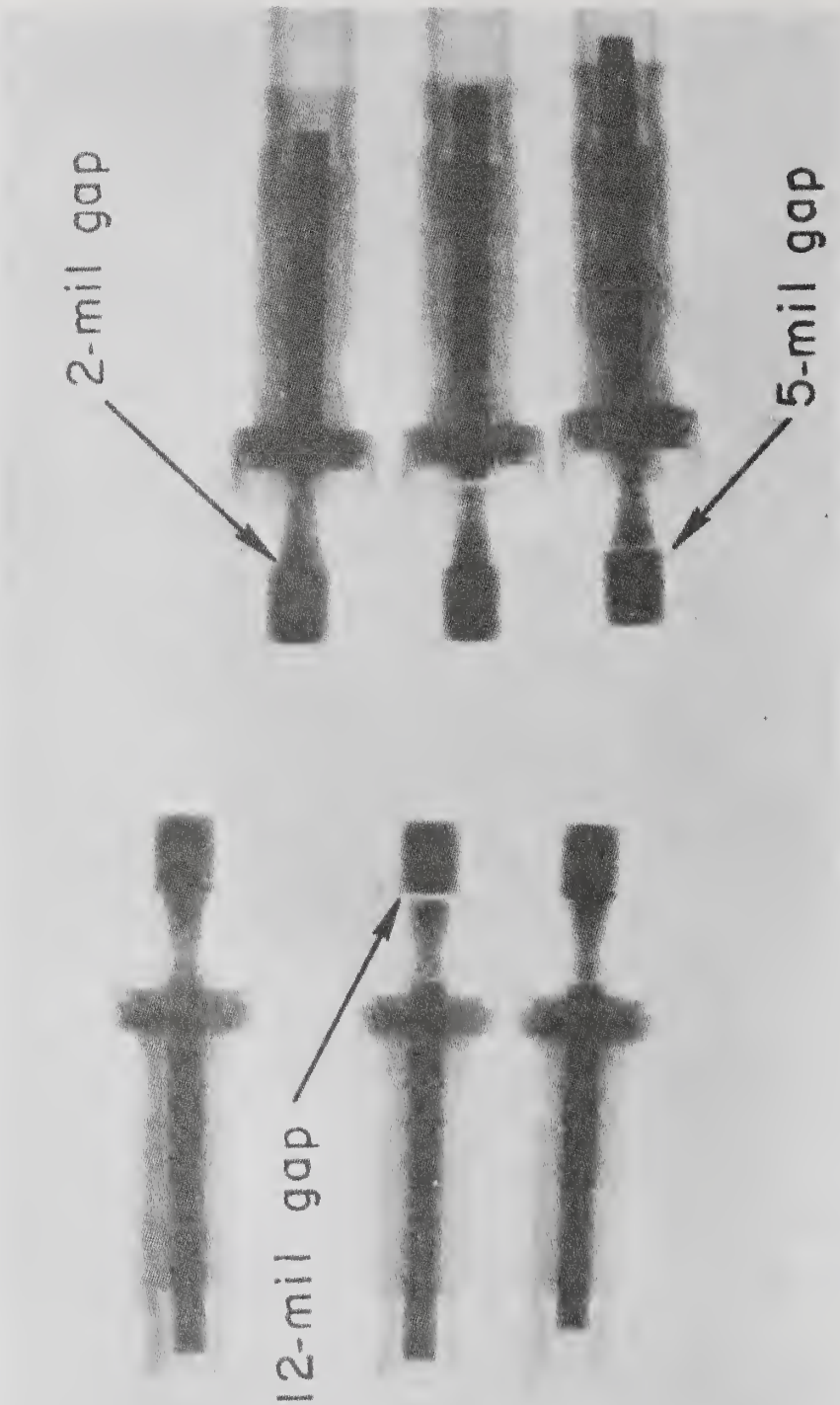

Figure 4. Enlarged print of neutron radiograph of shielded mild detonating cords with known defects (gaps of 12, 6, and 2 mils) identified by the arrows.

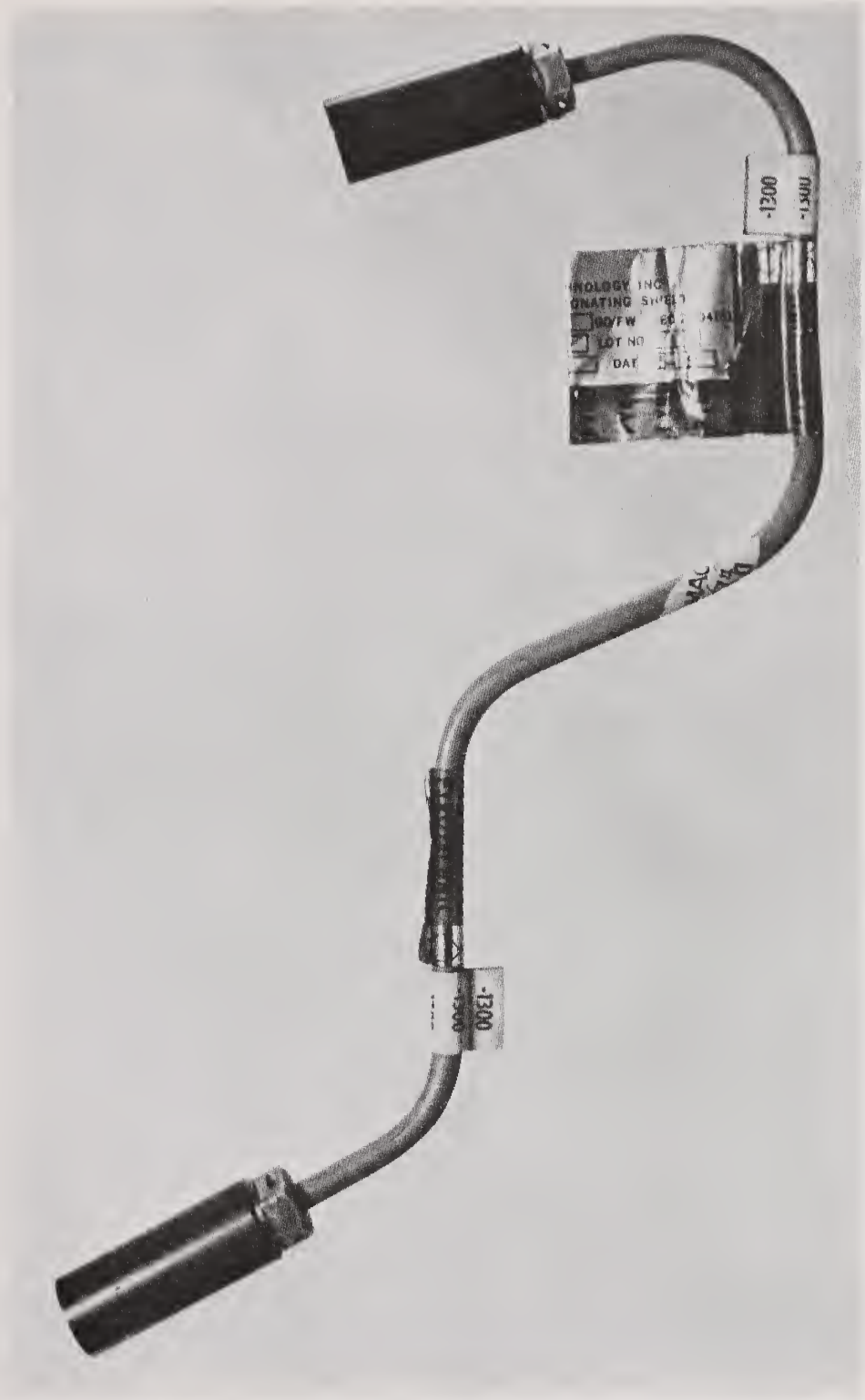

Figure 5. Photograph of pyrotechnic device used in the F-111 aircraft

Figure 6. Neutron radiograph of pyrotechnic device. The explosive material is clearly imaged through the metallic sheath.

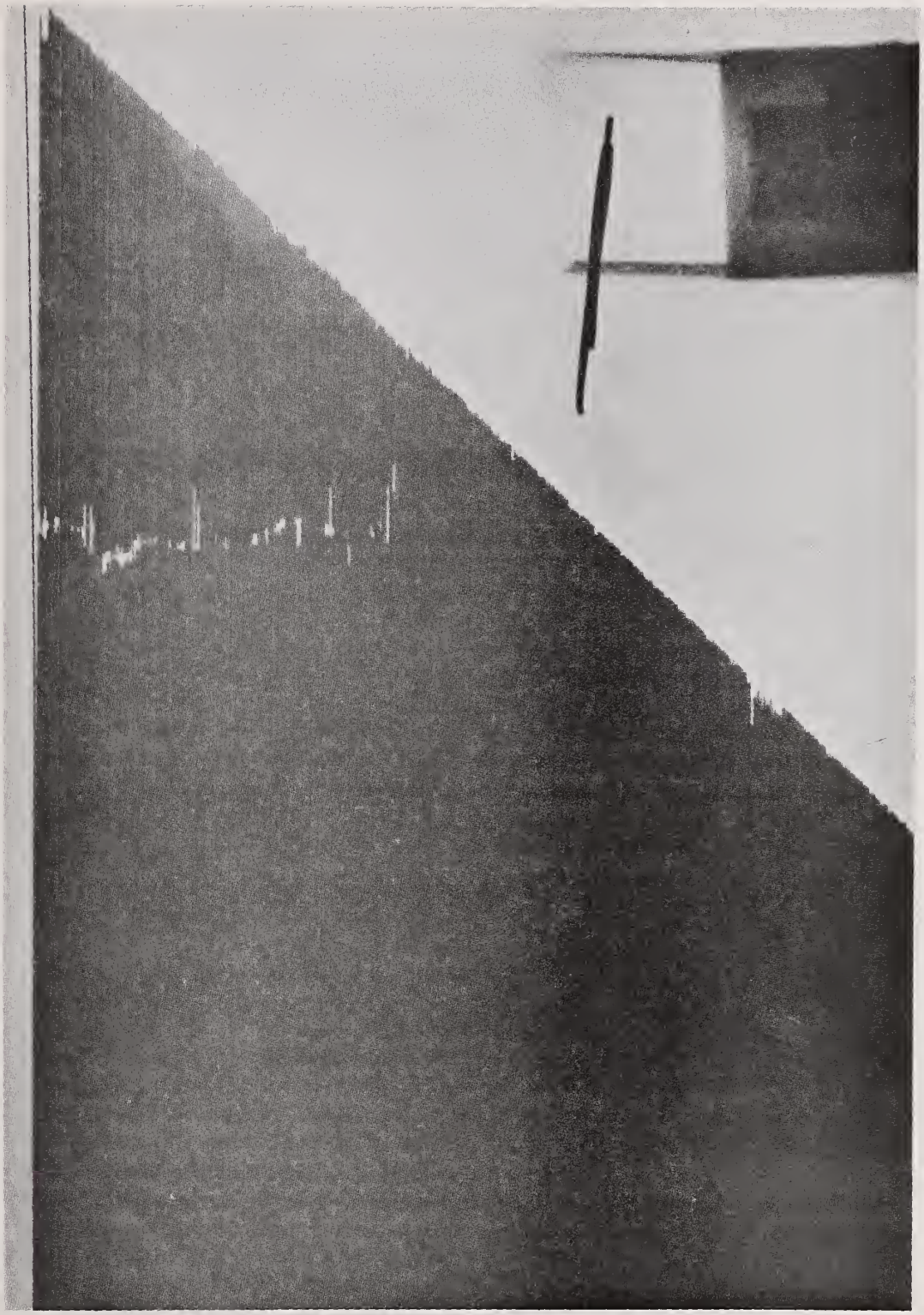

Figure 7. Enlarged print of neutron radiograph of tungsten-boron composite material consisting of 0.5-mil tungsten and 4-mil boron in aluminum matrix.

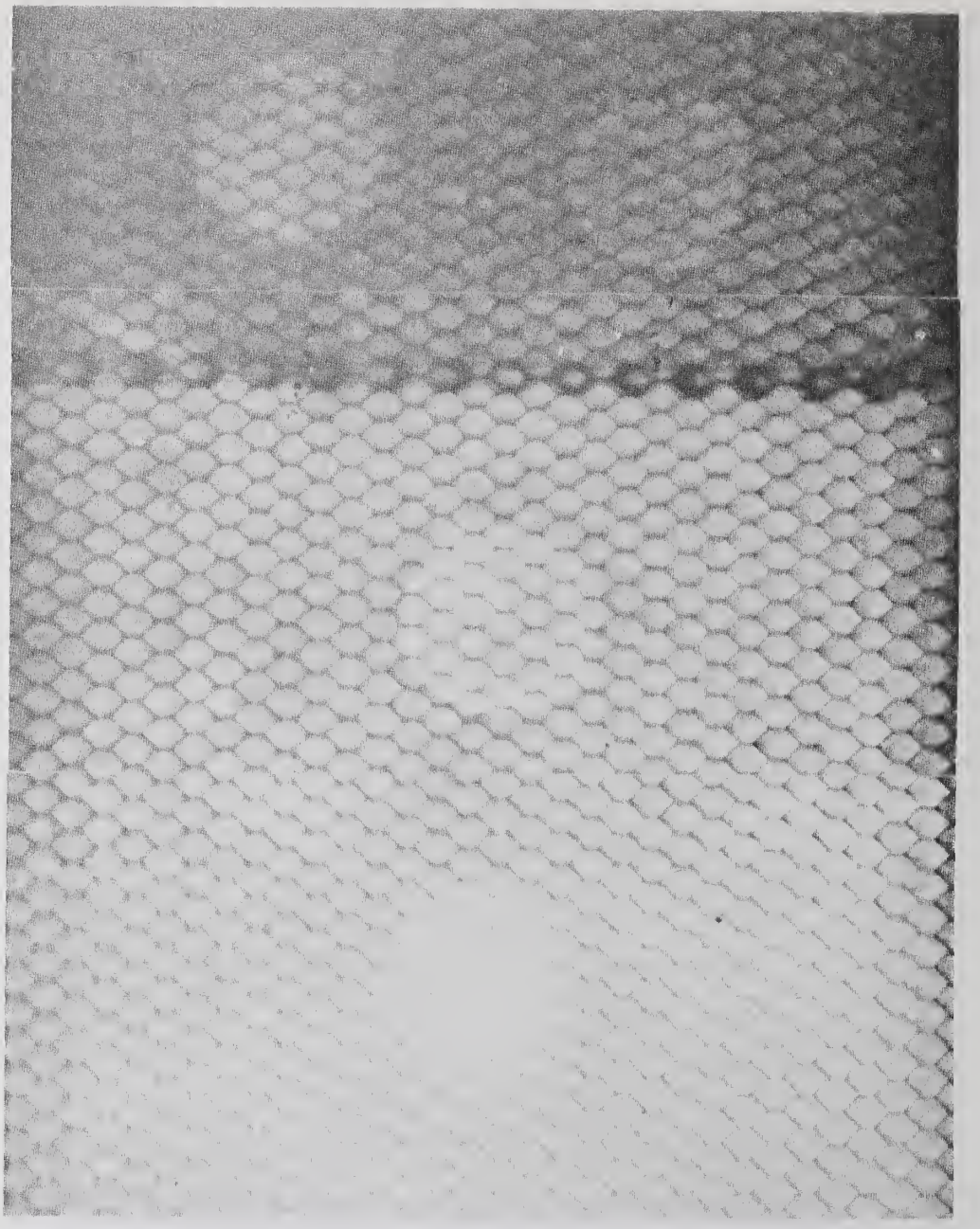

Figure 8. Neutron radiograph of an adhesively bonded test panel approximately 12 inches long, 7 inches wide, and 5/8 inch thick. The four circular areas seen in this figure are regions where no adhesive was applied to one of the end panels. The two circles with clearly defined edges are on the side of the panel close to the film, and the other two are on the opposite side of the panel. The honeycomb structure visible in this radiograph results from the adhesive around the metallic core rather than the core itself.

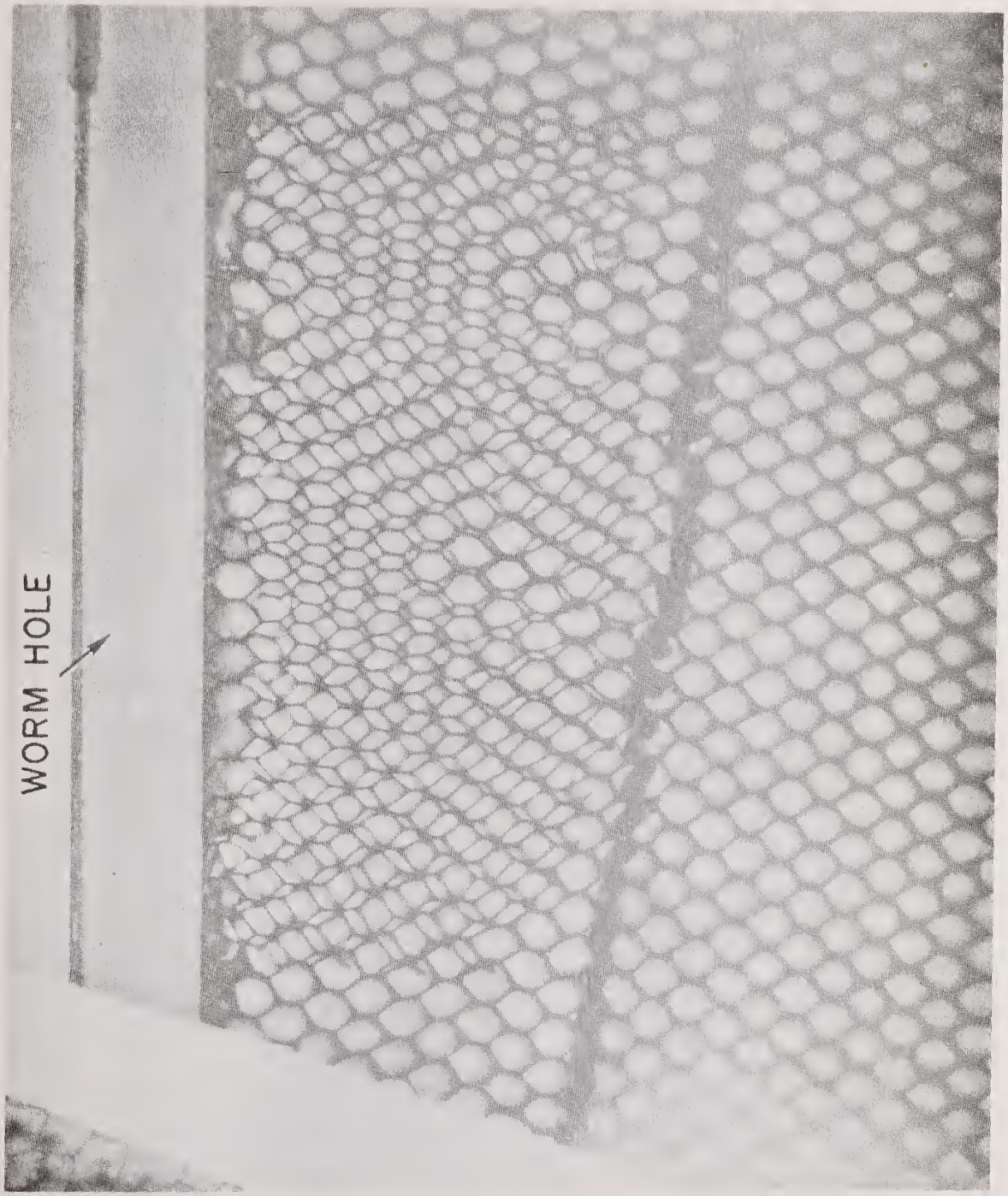

Figure 9. Neutron radiograph of a portion of the leading edge of the vertical stabilizer of an F-111 aircraft. The adhesive bond line between the aluminum arrowhead and the aluminum skin shows adhesive deficiencies providing possible leakage paths between the honeycomb cells and the outside environment. One such "worm hole" is labeled.

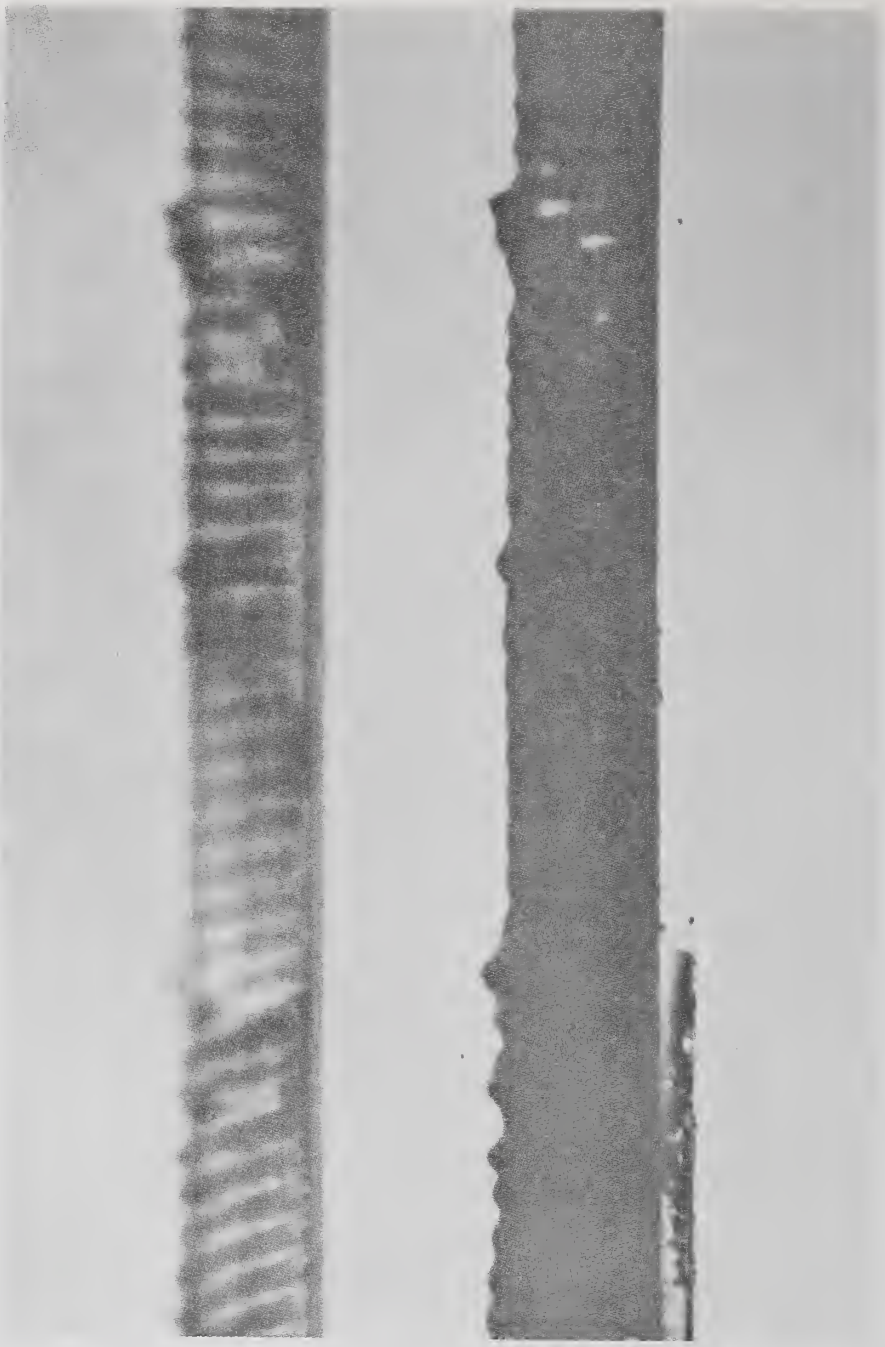

Figure 10. A composite of two neutron radiographs of a portion of a 540 helicopter blade system. The one at the left is a standard neutron radiograph showing the bond line between the C-spar and the spar closure clip, as well as the honeycomb. The one at the right shows the result after treatment with an enhancing agent. The penetration of the enhancing agent into the disbonded area helps clearly identify the extent of the disbond.

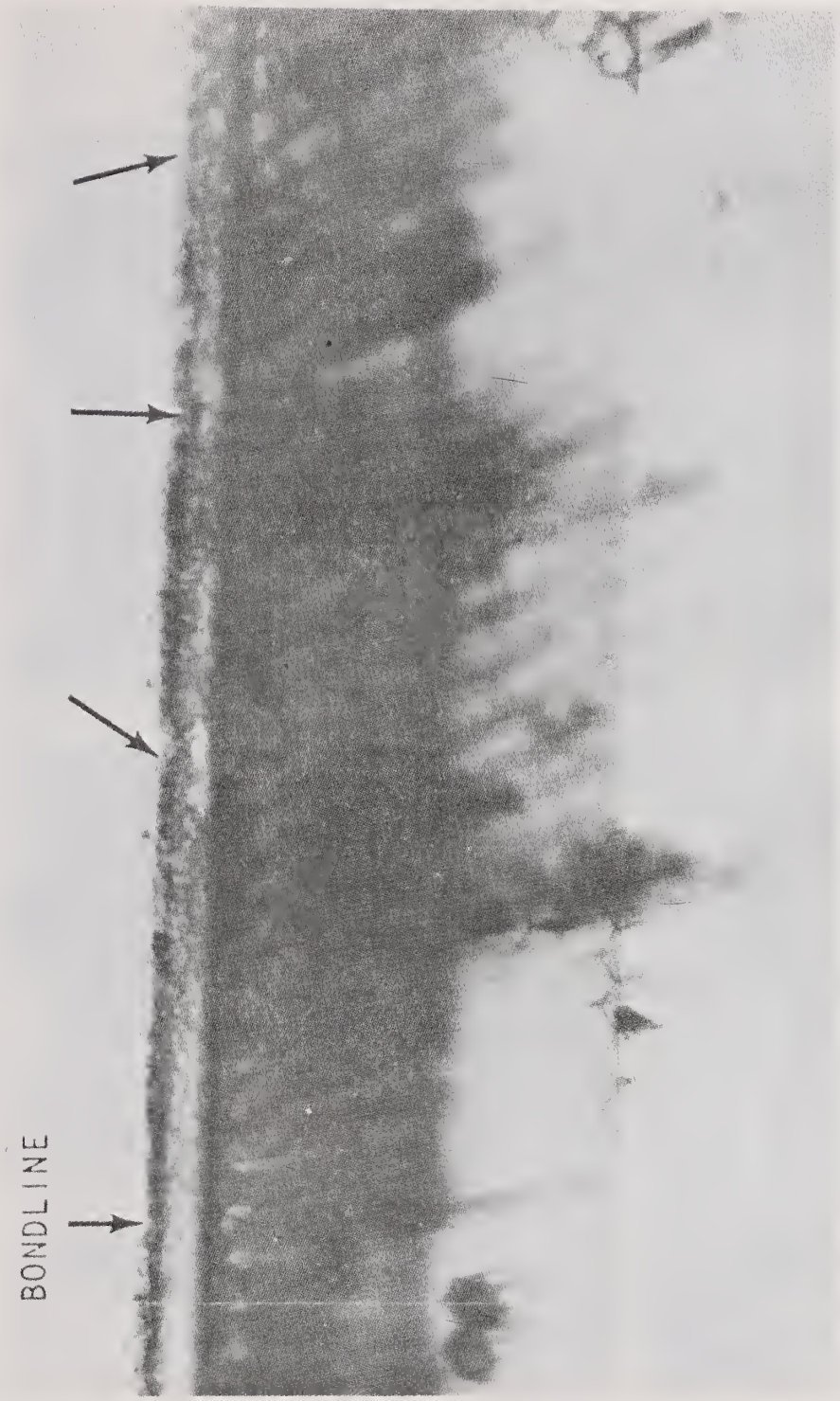

Figure 11. Neutron radiograph of a helicopter blade with fretting corrosion. The uneven nature of the bond line results from metal-to-metal contact due to inadequate quantities of adhesive.

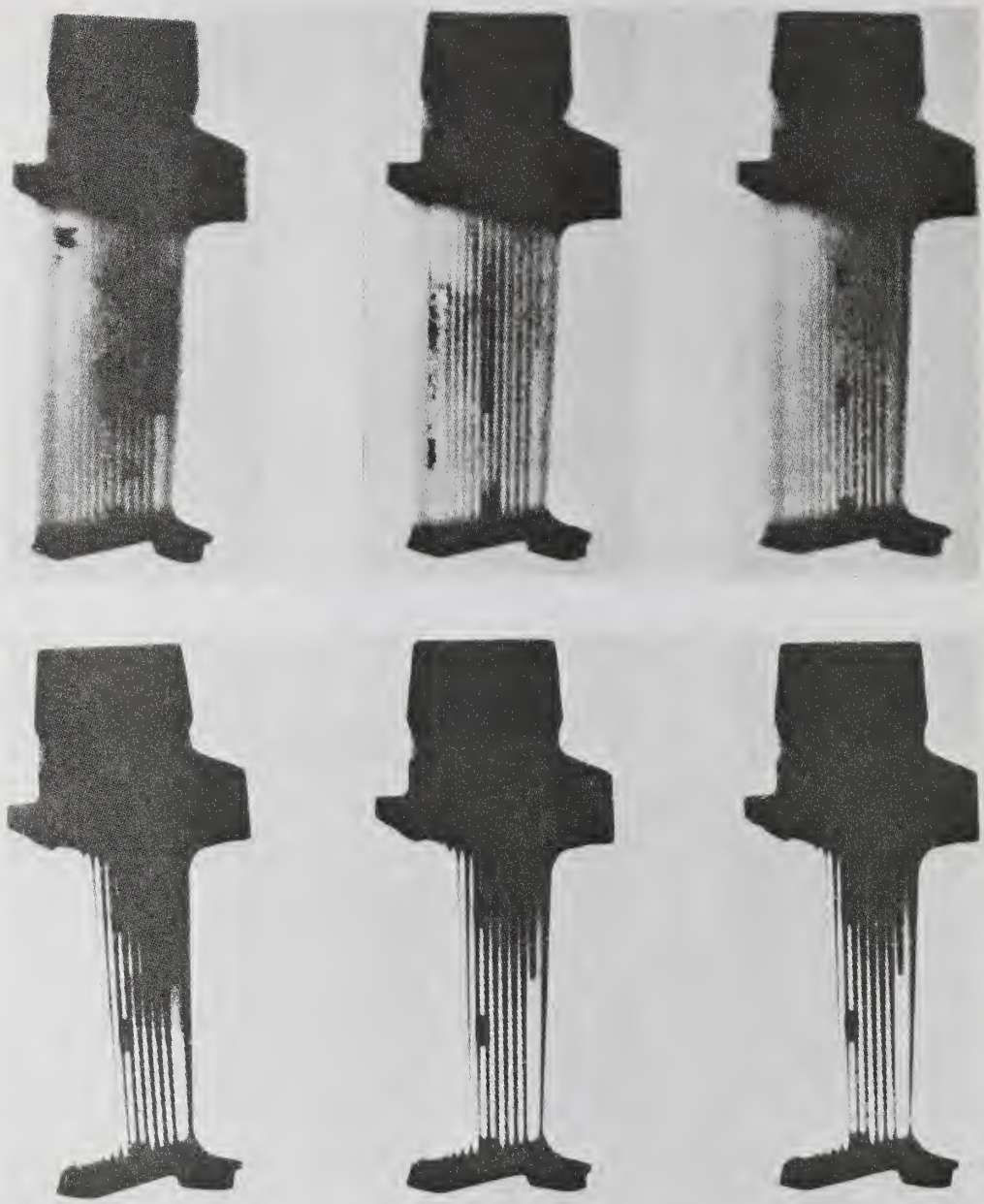

Figure 12. Comparison of x-radiograph and neutron radiograph for inspecting turbine blades for residual ceramic core. The set at the bottom is x-rays, and the one at the top was obtained with neutrons.

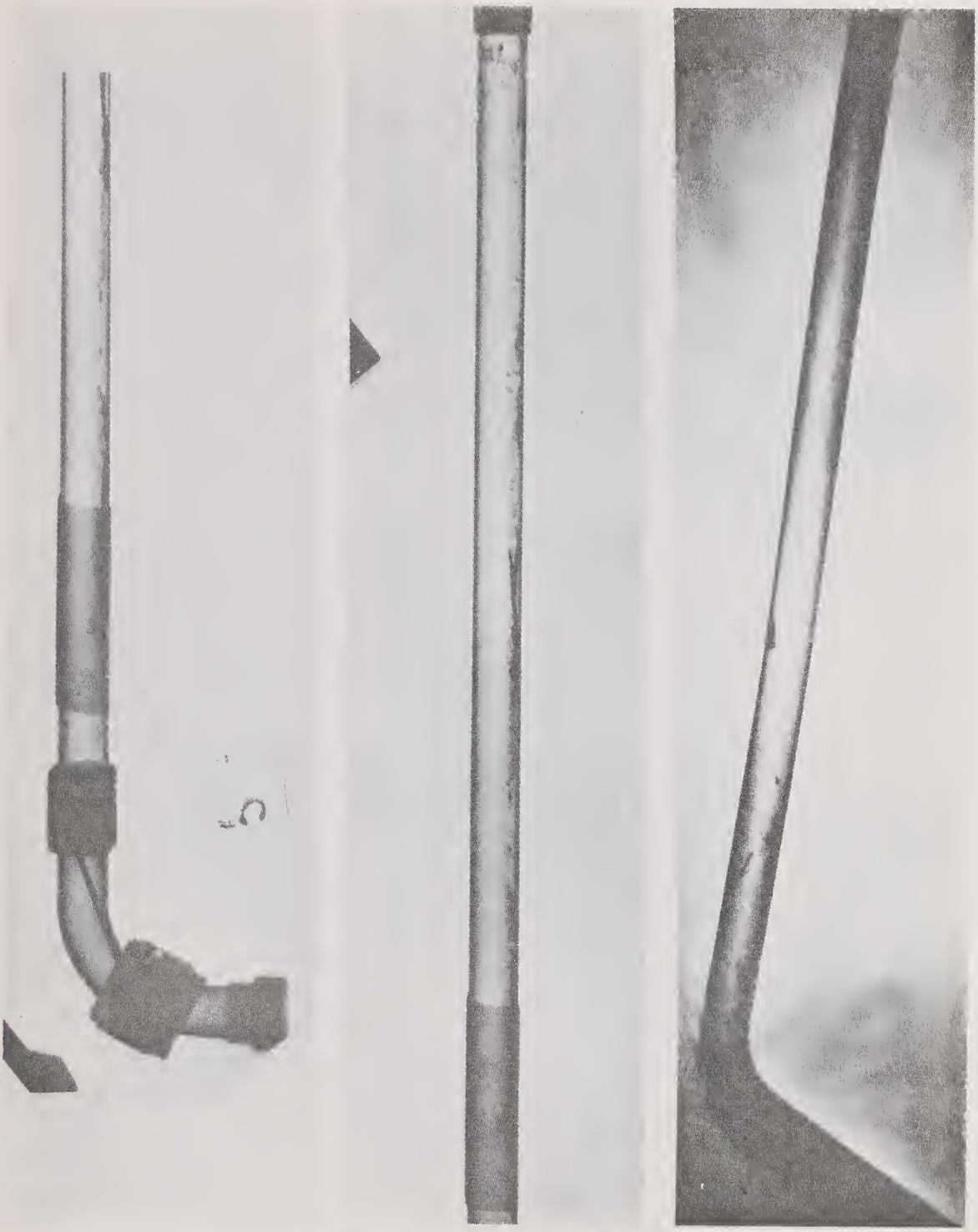

Figure 13. Neutron radiograph of portions of oil lines in aircraft engine showing coke deposits on the inner walls. A large piece of coke dislodged from the tube wall, is seen resting near the shoulder of the J-shaped tube.

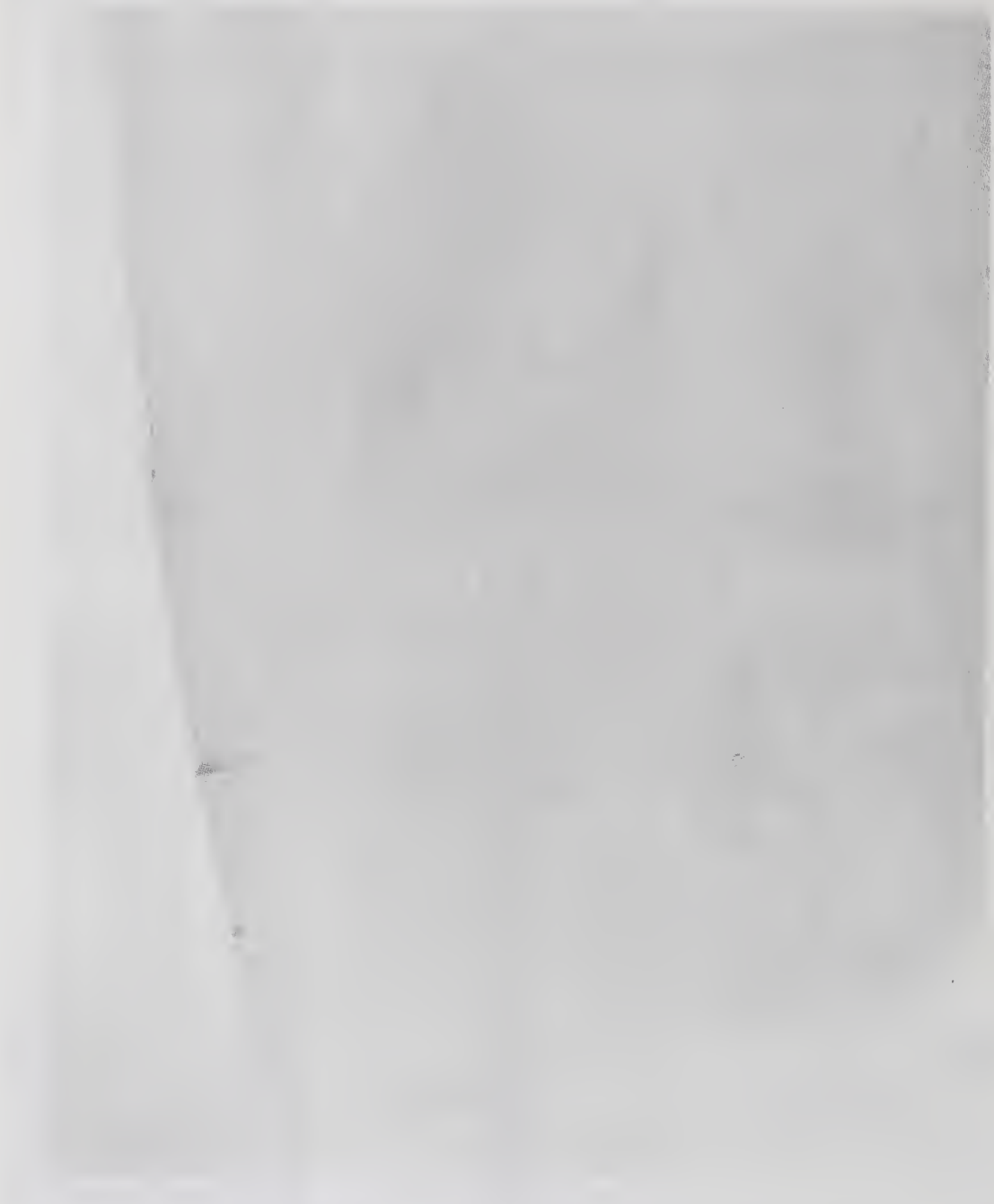

Figure 14. Neutron radiograph showing cracks at the tip of compressor blade of a TF-30 engine. The enhancing agent used in this case assists in defining the depth and orientation of the cracks.

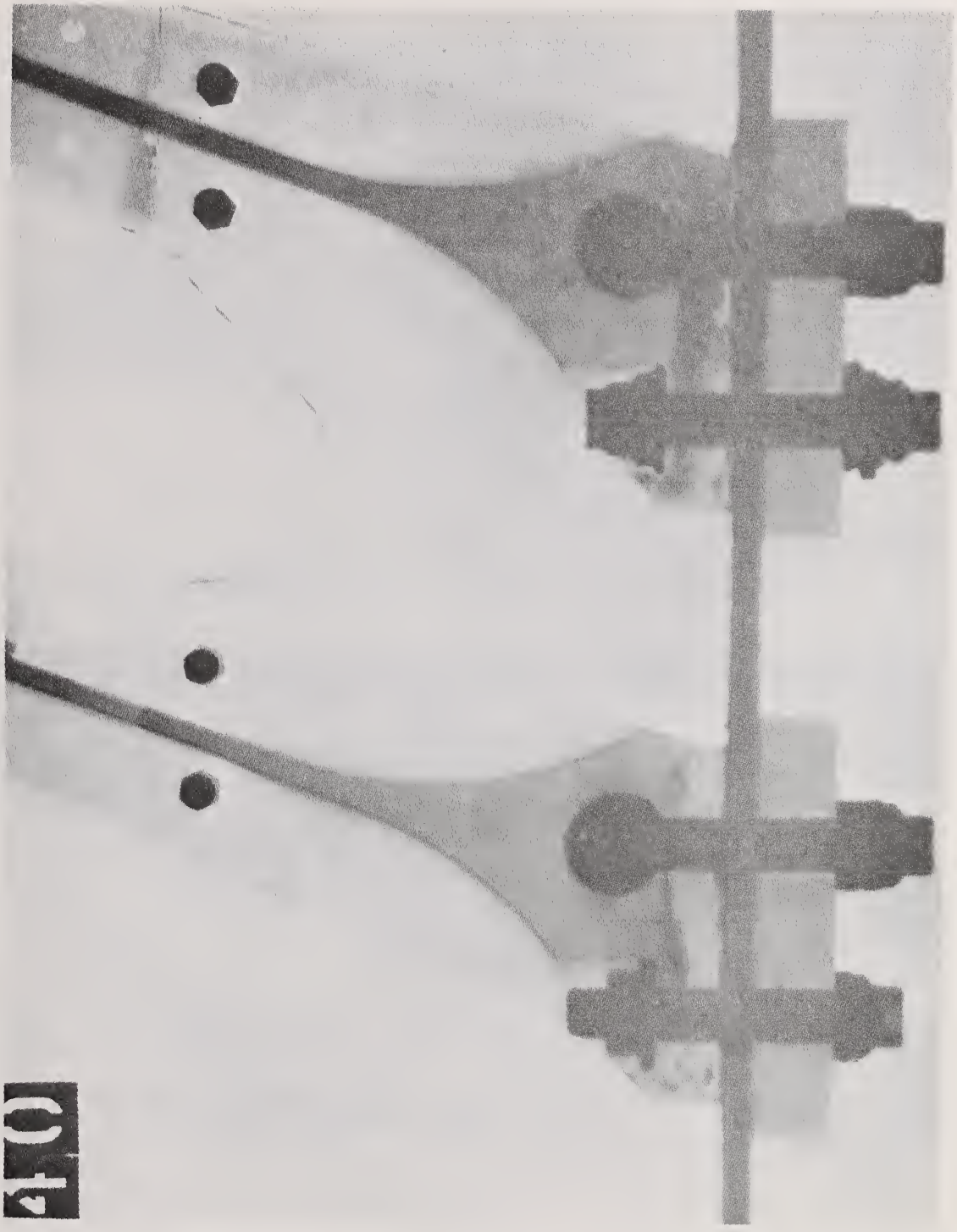

Figure 15. Neutron radiograph of a portion of the DC-9 wing tank showing the outline of the stringer, tee cap, and a set of bolts. The corroded area is visible through the stringer approximately two inches thick.

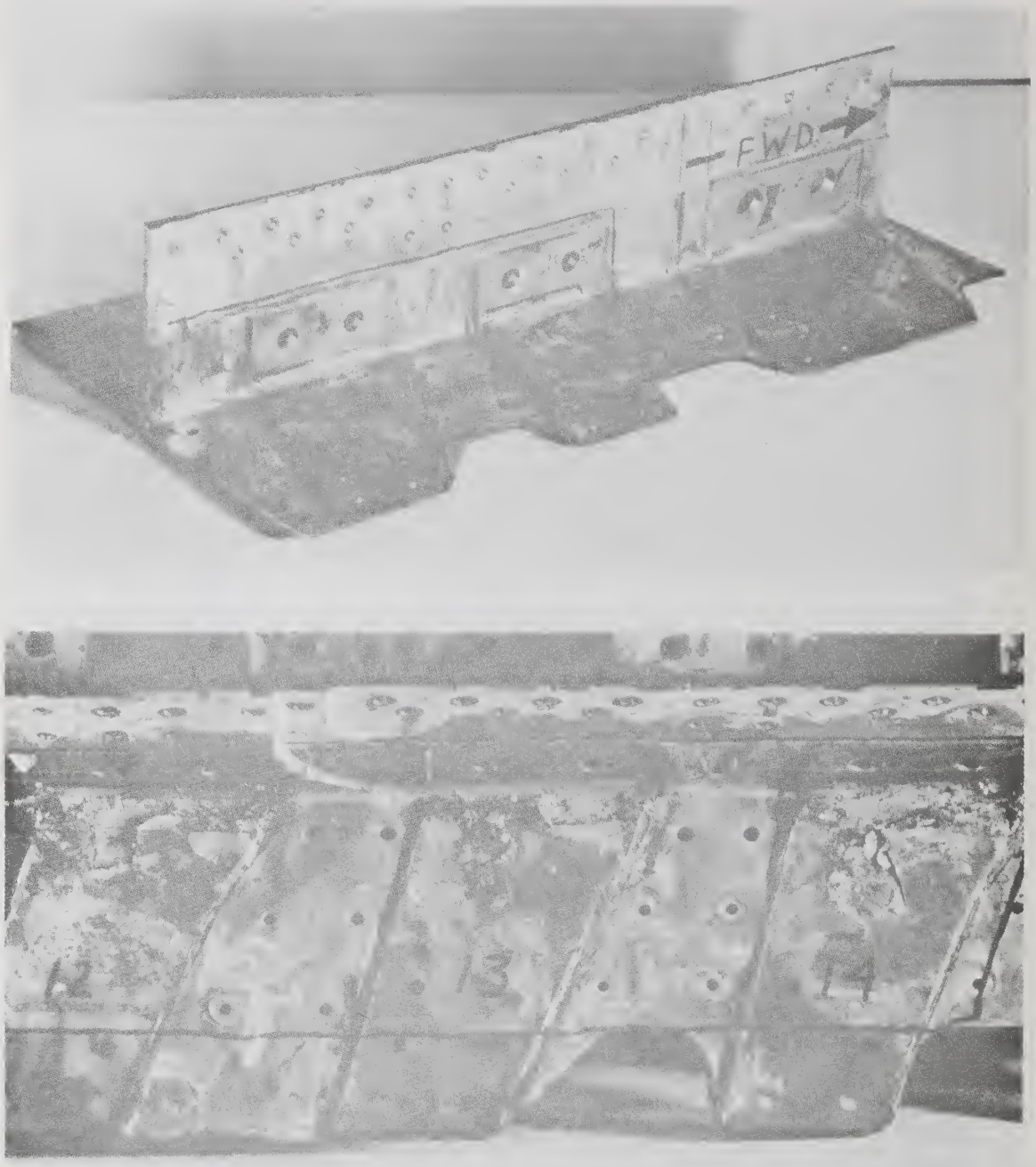

Figure 16. Photograph showing two views of the tee-cap surface from the DC-9 wing tank. Tee caps identified as 13 and 14 correspond to radiographs displayed in Figure 15.

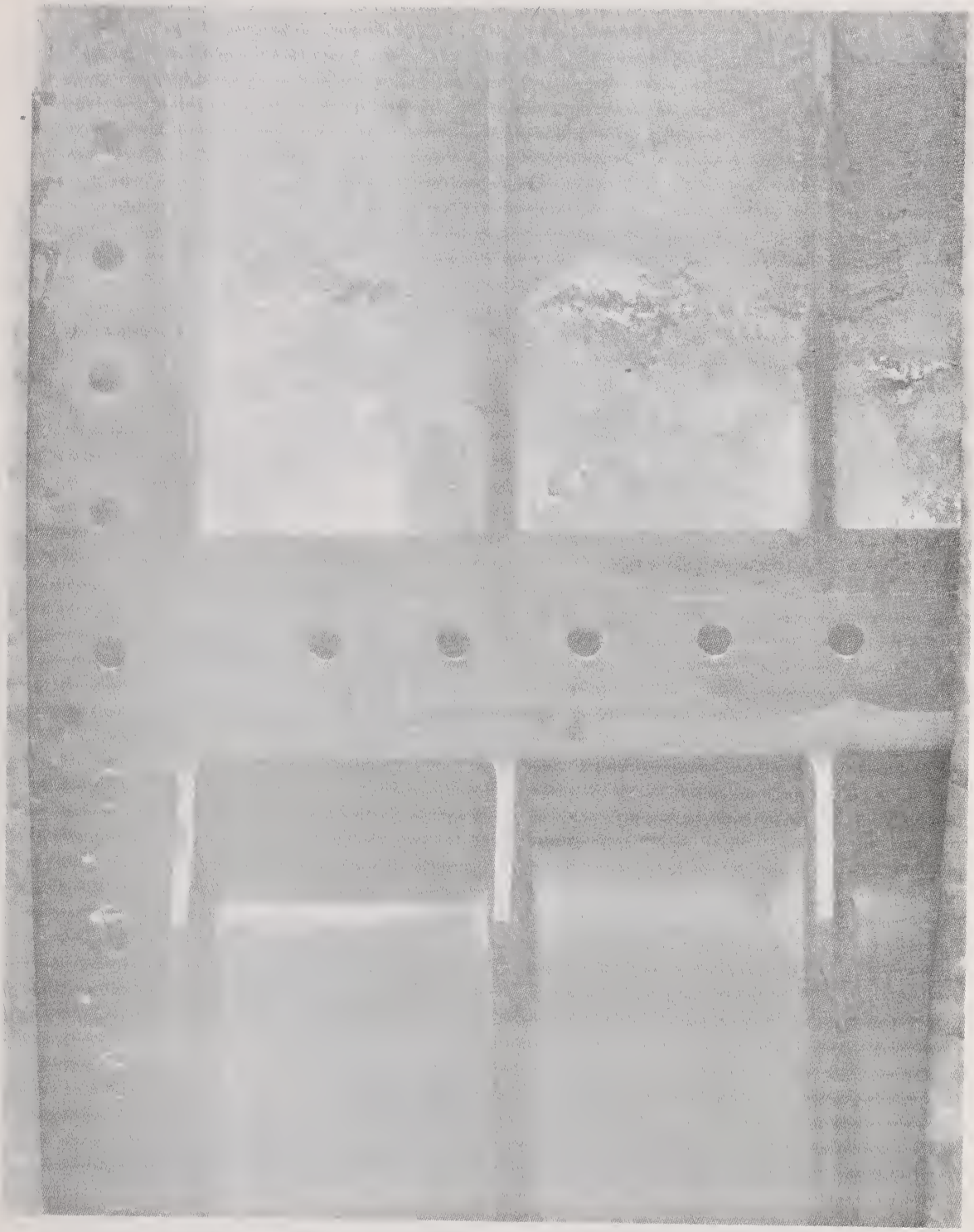

Figure 17. Photograph of a portion of the lower wing skin structure of a C-130 aircraft, showing the origin of the corrosion attack. The extent of corrosion is not clear from such visual inspection.

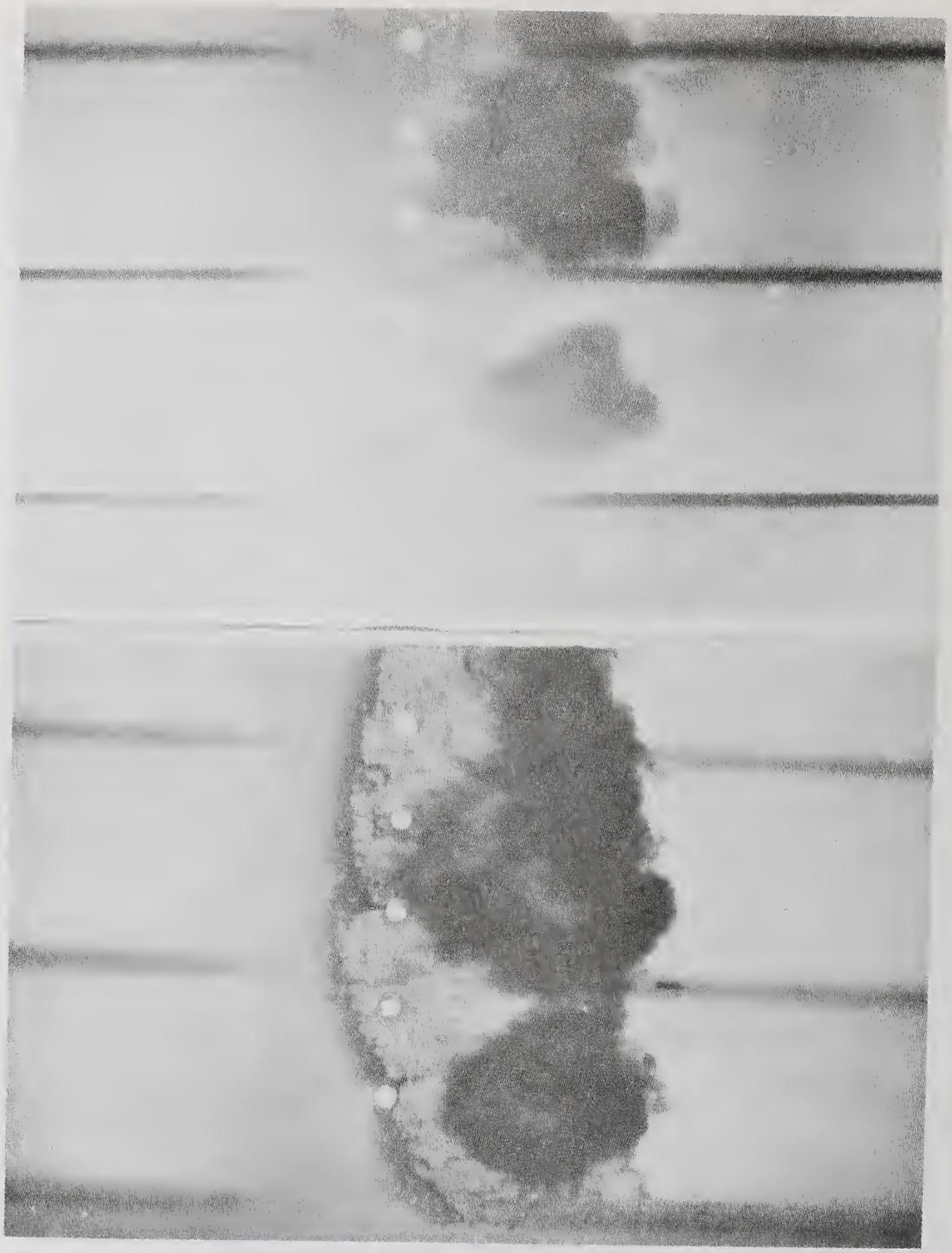

Figure 18. Neutron radiograph of C-130 wing structure. The neutron radiograph at the top is obtained in the usual way, and the one at the bottom with the use of a penetrant. The intergranular corrosion is seen to extend beyond the rivet holes, clearly explaining the cause of fuel leak from these holes.

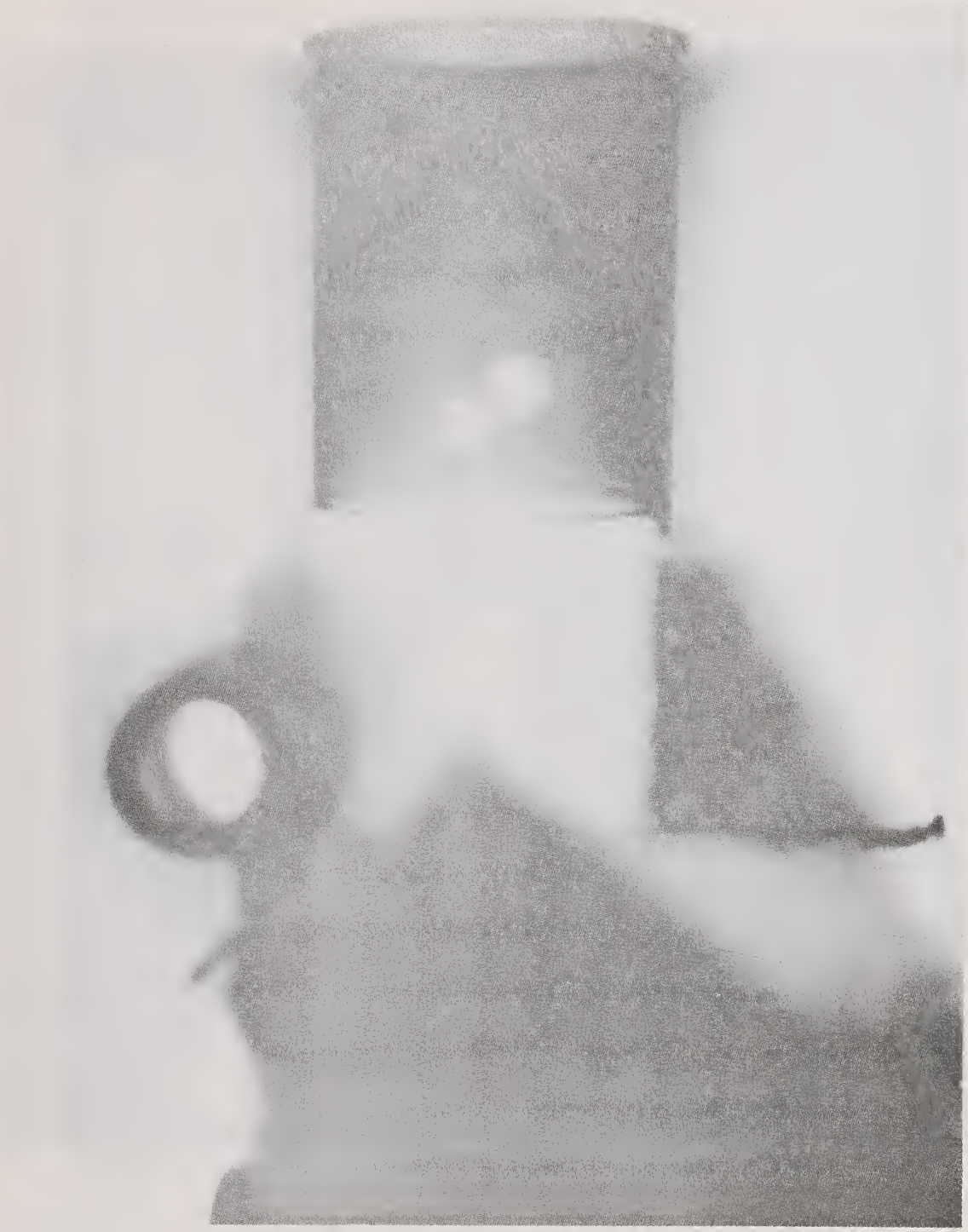

Figure 19. Neutron radiograph of an A-7 nose landing gear strut showing the extent, shape, and nature of stress-corrosion crack. This crack was barely visible, even after its location was confirmed by the eddy current technique.

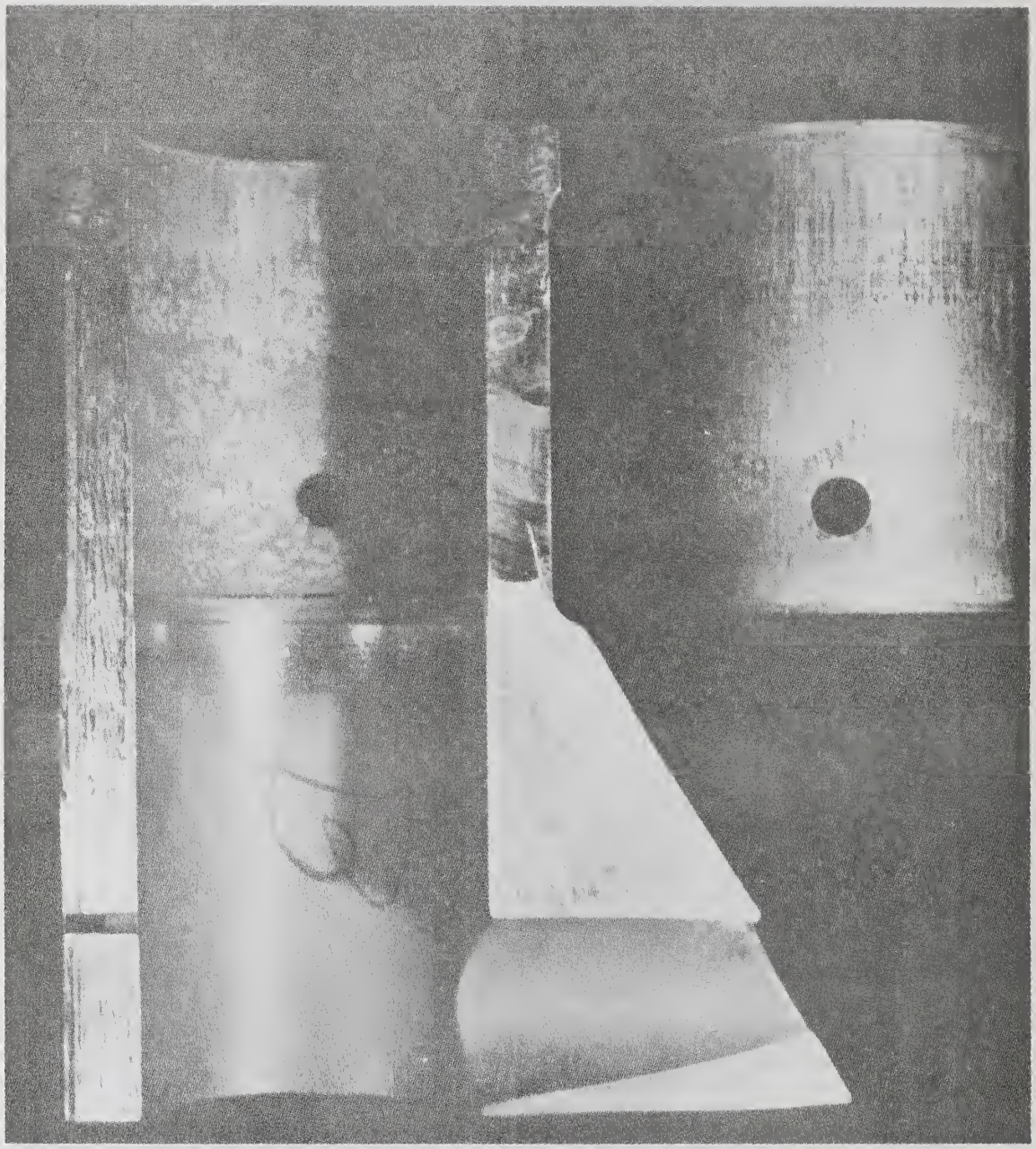

Figure 20. Photograph of the sectioned trunnion area showing the extent and shape of stress-corrosion crack

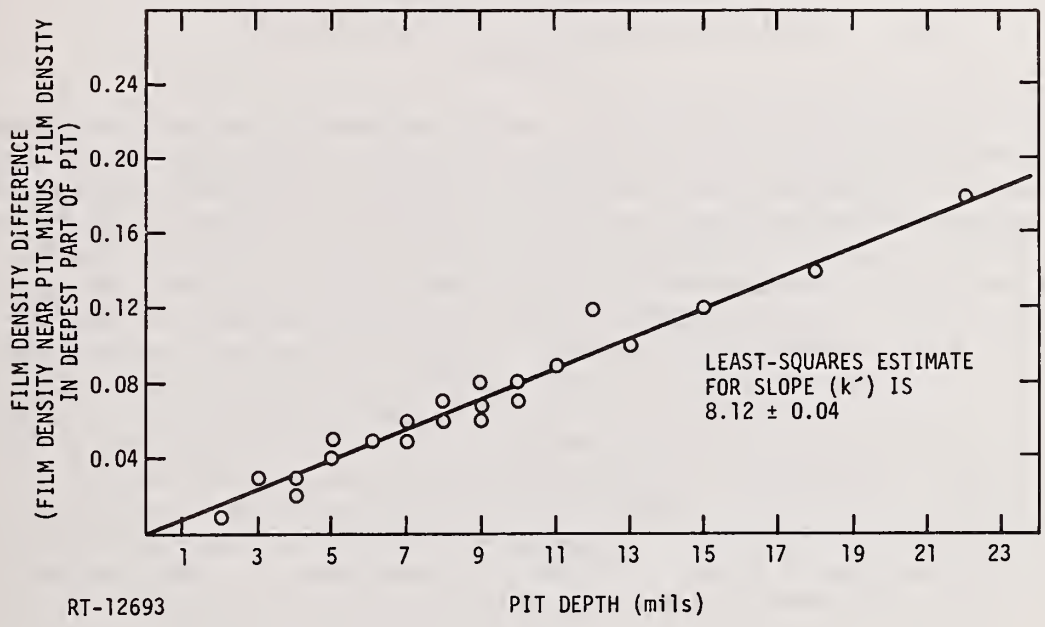

Figure 21. Graph of film density difference versus pit depth for corroded pits located on F-4 torque box panels (with AA film)

CREG™ EDDY CURRENT NDE: A COST EFFECTIVE APPROACH TO FAILURE PREVENTION

S. Sarian
Reluxtrol, Inc.
S. San Francisco, CA 49080

Abstract

State-of-the-art NDE practice for quality assurance and failure prevention relies basically on magnetic particle/penetrant, ultrasonic, and conventional eddy current techniques. Of these techniques, eddy current is the most attractive because it is versatile and can be applied to a wide spectrum of NDE problems - defect detection and sizing, coating thickness measurement, determination of heat treat/metallurgical condition such as hardness profile, dimensional measurement, to name a few - and it is especially amenable to rapid testing and screening of metal parts under production line conditions. In spite of its attractiveness, eddy current has not found widespread use because it suffers from edge effect which greatly reduces the effectiveness of the inspection in the vicinity of geometric tight spots, as well as lack of sensitivity, especially in the inspection of low conductivity titanium and nickel base alloys, and ferro-magnetic alloys because of problems with high background noise. Therefore, improvements in eddy current inspection performance are necessary to assure reliable micro-examination of materials and to avoid confusing the inspection because of false signals arising from material artifacts not conducive to the mechanical integrity - especially in production and maintenance environments.

There are three complimentary areas where improvements in early detection, identification, and sizing of metal distress can be made: (1) in the sensing element, (2) in the eddy current test instrumentation, and (3) in the signal data processing. It has been Reluxtrol's experience that the first of these areas is subject to greatest improvement in inspection performance. In this paper we describe the high-sensitivity, high resolution CREG™ focused field eddy current sensors and ancillary electronics to accomplish inspection of a wide variety of test parts under production line and field maintenance conditions.

DESIGN AND DEVELOPMENT OF A COLORIMETRIC FIELD TEST KIT FOR IRON WEAR METAL DETERMINATION

W. J. Hillan and W. D. Ross
Monsanto Research Corporation
Dayton, OH 45407

K. J. Eisentraut
Materials Laboratory
Wright-Patterson AFB, OH 45433

Abstract: A rapid, flight-line kit for the analysis of iron wear metal (a major wear indicator) in jet engine lubricants has been developed by Monsanto Research Corporation in conjunction with the U.S. Air Force. The Colorimetric Iron Kit (CIK) was developed to reduce the analytical lag time caused by sending all lubricating oil samples to an Air Force Oil Analysis Program (AF-OAP) laboratory. The CIK is portable, compact, light weight (25 pounds), and can be operated by nontechnical personnel.

The kit utilizes a colorimetric method which employs a solvent extraction-chelation procedure. Reagents required for the procedure are sealed in plastic tubes and along with all disposable items are packaged in analysis packets which are contained in the Colorimetric Iron Kit. The colored solution resulting from the analysis procedure is quantitated with a spectrophotometer.

A Hach DR/2 spectrophotometer has been modified to meet the specific requirements of the CIK. The required wavelength is preset and the meter scale reads directly in parts-per-million iron. Designed to analyze concentrations between 0 and 50 ppm iron, the kit contains all required components in a 23.5 x 10 x 8.5 inch carrying case.

Six kits and 1,500 analysis packets were successfully field tested by the Air Force in the United States. Currently six kits and 2,000 analysis packets are being tested by the U.S. Air Force in Europe.

Key words: Colorimetric iron kit; iron; jet engine oil; portable; rapid; wear-metal analysis.

The U.S. Air Force currently uses the Air Force Oil Analysis Program (AF-OAP) to analyze its used jet engine lubricating oils to detect abnormal engine wear. There are approximately 120 AF-OAP laboratories located throughout the Air Force which employ atomic absorption or atomic emission methods to analyze the used oil samples. The principal thrust of the AF-OAP program is to prevent engine failure by predicting engine wear from the results of the wear-metal analyses.

However, there are several drawbacks to this procedure. Every sample tested at an AF-OAP laboratory receives detailed, multielement analysis. The AF-OAP labs are generally located away from the flight-line and since there is not a lab at every operational base, the samples, in some instances, must be sent off-site for wear-metal analysis. More specifically, European maneuvers often demand remote site aircraft operations which require oil samples to be flown to an AF-OAP lab for analysis. As a result of these facts, a lag time is created between the time the sample is removed from the aircraft and the time the corrective action dictated by the AF-OAP lab results can be implemented. In some cases this lag time may be too long and corrective action may be too late to prevent engine failure.

Therefore, the Air Force requires a rapid, on-the-spot test for a major wear-metal. The test should also be simple, inexpensive, portable, and able to be done at the flight-line or remote sites by maintenance personnel. The test would be a supplement to the current oil analysis program and would be used in specific cases where AF-OAP labs were not readily available or instantaneous results were required.

We have developed the Colorimetric Iron Kit (CIK) to fill this Air Force need. The kit utilizes a colorimetric procedure we developed to determine the iron content of used oil samples. The procedure is based on the concept of analysis by solvent extraction-chelation (SEC). This concept generally involves four common steps performed in varying order for different methods:

(1) Extraction of all iron into an immiscible layer,
(2) Conversion of iron to an appropriate oxidation state,
(3) Chelation with a colorimetric indicator, and
(4) Determination of color intensity.

The SEC method was modified and improved many times during the course of the research. The reagents and procedure described below are the result of these improvements and the procedure is the one employed in the CIK.

Reagents

(1) H_2SO_4 solution - 7.6 mL concentrated H_2SO_4 + 63.6 mL iron-free deionized H_2O + 28.8 mL ethanol.

(2) Isoamyl alcohol - reagent grade.

(3) Buffer solution - 50 g sodium acetate dissolved in iron-free deionized water by diluting to 100 mL.

(4) Reducer solution - 40 g hydroxylamine hydrochloride dissolved in iron-free deionized water by diluting to 100 mL.

(5) Indicator solution (0.019M) - 0.1 g bathophenanthrolinedisulfonic acid in 10 mL iron-free deionized water.

Procedure

Step 1. To 1 mL of 3N H_2SO_4 solution and 2 mL of isoamyl alcohol in a 1-oz French square bottle, add 1 mL of used oil. Shake for 2 min on a vortex mixer.

Step 2. Add 1 mL of the buffer solution and 0.5 mL of reducer solution. Shake for 1 min.

Step 3. Add 0.5 mL of 0.019M indicator solution. Shake well for 1 min and allow the phases to separate.

Step 4. Add 21 mL of iron-free deionized water and test on a Hach DR/2 spectrophotometer at 530 nm.

The red coloration of the lower aqueous layer is indicative of the iron concentration.

Many reagent packaging systems were investigated and the system shown in Figure 1 was selected for use in the CIK. The system shown in Figure 1 is packaged in a 5-in. x 5-in. Zip-Lip® polyethylene bag. All one-time-use items are contained in this bag and can be returned to the bag after use for disposal. The reagents are sealed in polyethylene tubes. The bag contains the following items, numbered to correspond to the numbers in Figure 1:

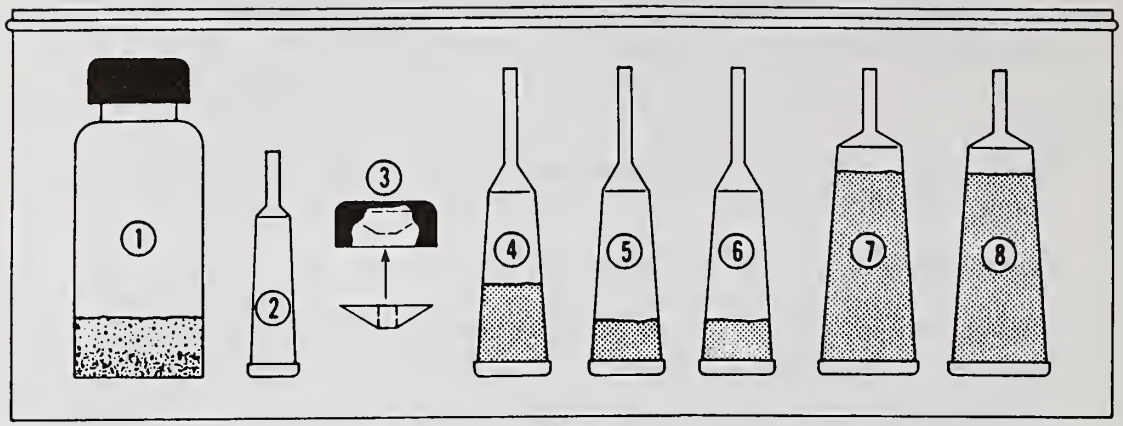

Figure 1. Reagent packaging system for the Colorimetric Iron Kit (CIK).

(1) One 1-oz French square bottle containing 1 mL H_2SO_4 solution and 2 mL isoamyl alcohol.

(2) Pipette tip for the oil pipette.

(3) Plastic cap (with hole in top) and cap liner (with hole to fit reagent tubes).

(4) Tube containing 1 mL of buffer solution.

(5) Tube containing 0.5 mL of reducer solution.

(6) Tube containing 0.5 mL of indicator solution.

(7) and (8) Two tubes, each containing 10.5 mL of deionized water.

The 1-oz French square bottle was chosen to serve as both the reaction vessel and test cell because it is inexpensive, and it fits the specimen chamber of the Hach DR/2 spectrophotometer used for the field test kits.

The Hach DR/2 spectrophotometer was chosen to be used in the CIK because it fits our needs better than other commercially available instruments. That is, it is relatively low in cost, has its own large carrying case, and

can operate on either 115-V alternating current or on battery power (self-contained). The square specimen chamber that allows us to use the 1-oz French square bottles is also an important feature.

Figure 2 shows the Colorimetric Iron Kit. The following modifications were made to the spectrophotometer to meet the specific requirements of the CIK:

(1) The variable interference light filter was fixed at 530 nm.

(2) The variable zero adjust and light adjust knobs were replaced by locking screwdriver-driven adjust knobs.

(3) The removable scale card on the meter was replaced by a permanent card that reads directly in parts per million (ppm) iron.

(4) A plastic cover was placed over the wavelength thumbwheel to protect the interference filter from spills.

In addition, a timer which controls the vortex mixer was permanently wired into the spectrophotometer, and the vortex mixer was plugged into the timer. Therefore, only one power supply cord is required to operate the spectrophotometer, timer, and mixer. A holder for the screwdriver and stainless steel scissors was fitted into the large compartment on the spectrophotometer face. The screwdriver is used to adjust the zero adjust and light adjust knobs, and the stainless steel scissors are used to cut the tips off of the reagent tubes. The timer is fastened to the right-hand compartment of the carrying case, and the vortex mixer, power supply cord, and safety goggles are stored there also. The left-hand compartment is reserved for the 12 analysis packets and microwipe tissues supplied with the kit. The lid was modified to accommodate the laminated step-by-step instruction sheet (see Figure 3) in the left-hand side. Also included in the lid are the oil pipette and the color comparison chart. The color comparison chart is intended for use only in the event the spectrophotometer becomes inoperable.

A detailed operating manual was prepared and a copy was included with each kit. The pages of the manuals were laminated for protection from oil and chemical spills and other possible flight-line hazards.

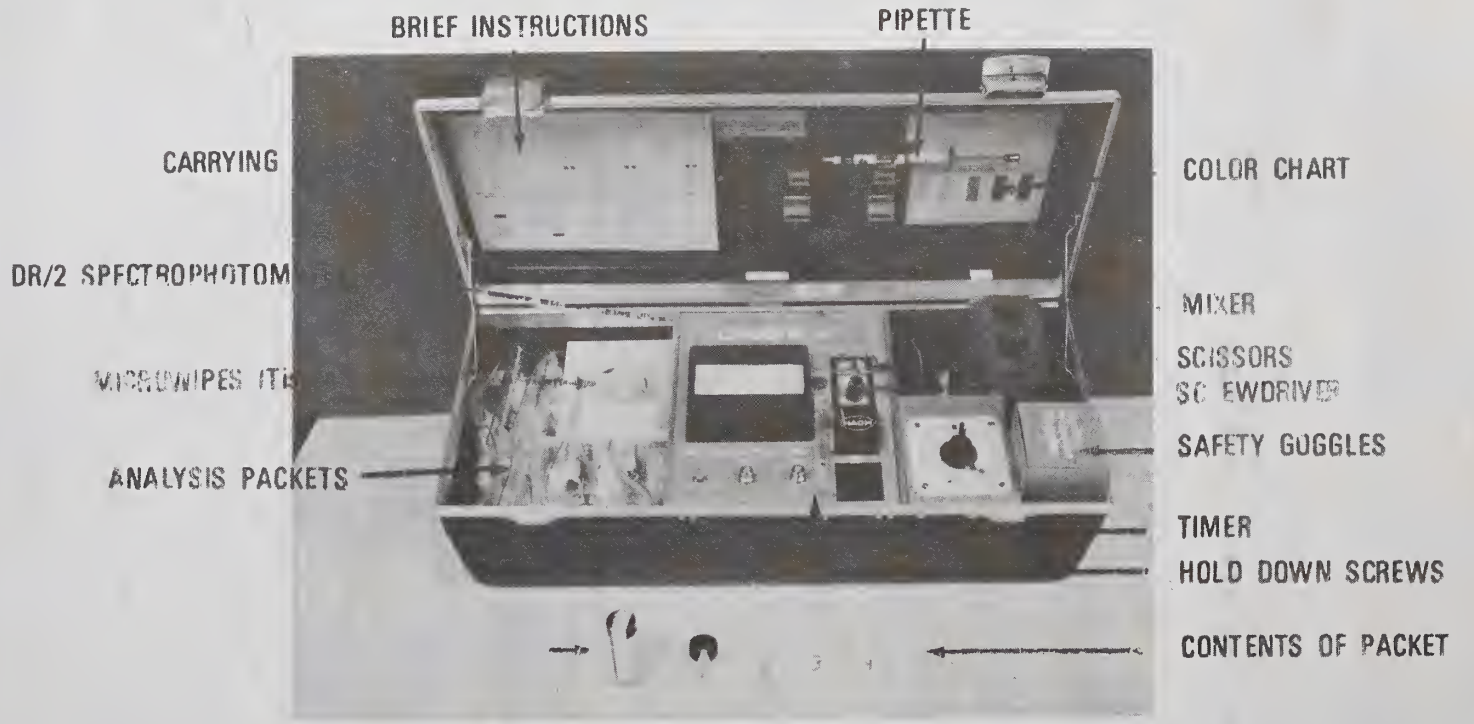

Figure 2. Colorimetric oil analysis field test kit.

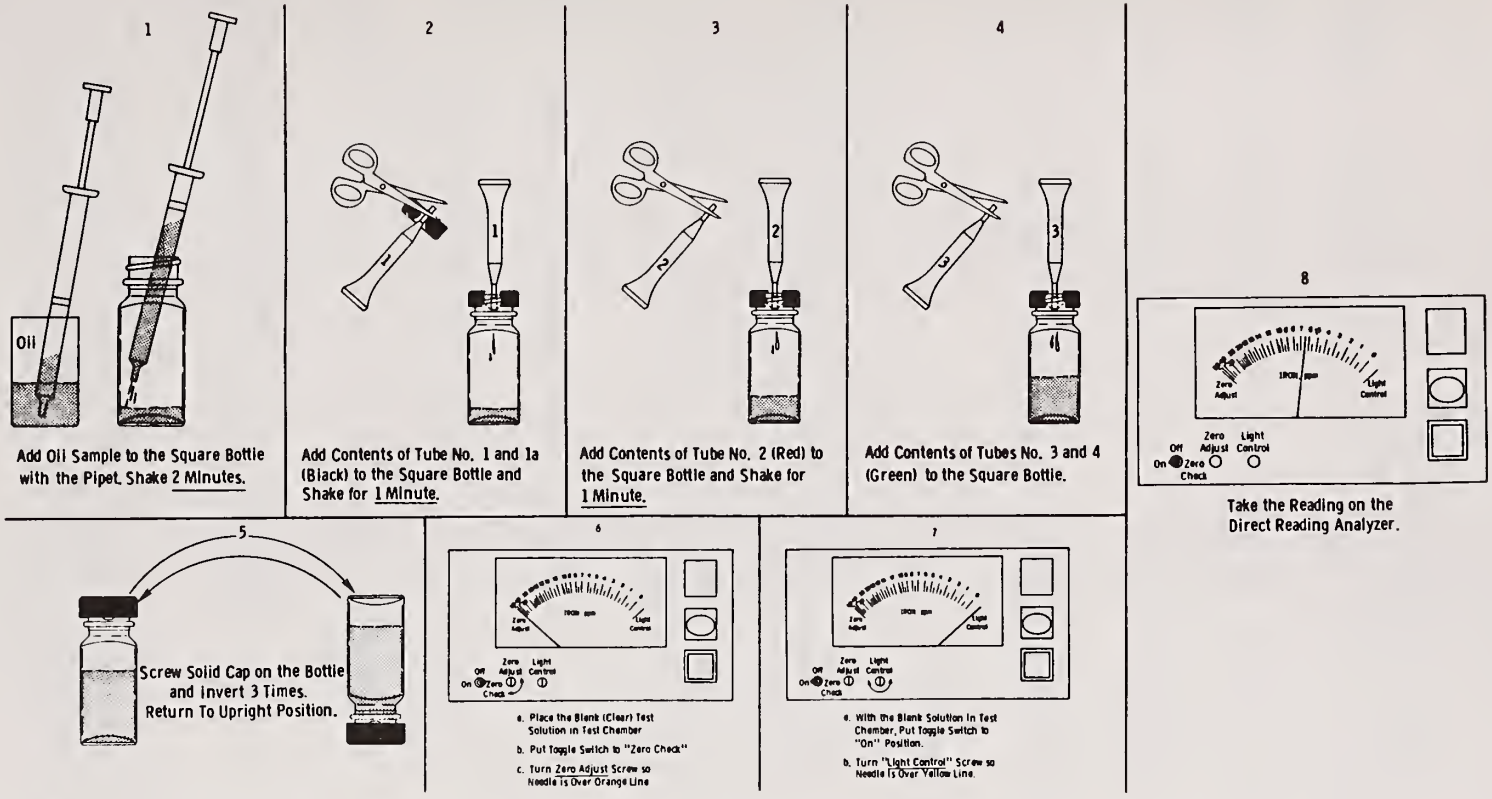

Figure 3. Pictorial step-by-step instruction sheet for the colorimetric method.

During the course of this research several actual used oil samples were analyzed by the colorimetric method. Atomic absorption, colorimetric, and particle size independent data for 29 used oil samples are compared in Table 1. The particle size independent method was developed at the Air Force Materials Laboratory to minimize the effect of large metal particles on the analysis of used jet engine oils for wear metal content.

Comparison of the atomic absorption and colorimetric data in Table 1 shows the following:

(1) The colorimetric data were >1 ppm higher for 13 samples.

(2) The colorimetric and atomic absorption data were equal (<1 ppm difference) for 13 samples.

(3) The colorimetric data were >1 ppm lower for three samples.

Since the first Air Force field test for the colorimetric kit was done on aircraft engines which have threshold limits of 8 ppm iron, particular attention was paid to used oil samples containing <15 ppm iron. Table 2 displays the comparative results for 19 used oil samples analyzed by atomic absorption, particle size independent, and the five-step colorimetric method using 3N H_2SO_4. Comparison of the colorimetric and atomic absorption data show the following:

(1) The colorimetric data were higher (>1 ppm higher) for four samples.

(2) The colorimetric and atomic absorption data were equal (<1 ppm difference) for 12 samples.

(3) The colorimetric data were lower (>1 ppm lower) for three samples.

This shows that the colorimetric and atomic absorption data agree very well for oil samples containing less than 15 ppm iron.

In summary, when considering Tables 1 and 2, it can be said that the 3N colorimetric method did better than atomic absorption (AA) analysis in 48% of the samples analyzed, and as well as or better than AA in 90% of the samples analyzed.

TABLE 1. COMPARATIVE RESULTS FOR IRON ANALYSIS OF USED OIL SAMPLES BY ATOMIC ABSORPTION, COLORIMETRIC, AND PARTICLE SIZE INDEPENDENT METHODS

Sample Number	Iron Content (ppm) Atomic Absorption	Colorimetric 3N Acid	Particle Size Independent
P-44	35.1	43.6	-
P-62	26.3	29.4	28
P-64	26.0	30.4	27
P-65	15.0	15.3	16
P-78	11.8	9.8	16
P-81	6.5	3.7	-
P-86	7.1	6.6	10
P-87	2.9	3.7	-
P-88	33.9	40.8	42
P-90	12.4	12.2	13
P-91	11.0	19.5	19
R-424	12.7	14.3	13
R-429	6.5	5.9	-
R-437	2.0	1.3	-
R-443	7.0	6.5	-
R-452	3.1	2.8	-
H-51	16.8	18.7	-
H-58	2.0	1.4	3
H-63	20.7	26.6	25
H-64	7.6	8.2	10
H-65	12.3	13.3	18
H-68	7.7	7.2	9
F-17	30.9	58.2	49
F-18	60.5	44.5	115
F-23	16.1	55.9	64
F-34	6.2	5.7	7
F-37	3.3	9.6	13
F-38	3.2	2.1	5
F-39	22.0	27.1	33

TABLE 2. COMPARATIVE RESULTS FOR IRON ANALYSIS OF USED OIL SAMPLES CONTAINING <15 ppm IRON BY ATOMIC ABSORPTION, COLORIMETRIC, AND PARTICLE SIZE INDEPENDENT METHODS

Sample Number	Iron Content (ppm) Atomic Absorption	Colorimetric (3N Acid)	Particle Size Independent
P-65	15.0	15.3	16
P-78	11.8	9.8	16
P-81	6.5	3.7	-
P-86	7.1	6.6	10
P-87	2.9	3.7	-
P-90	12.4	12.2	13
P-91	11.0	19.5	19
R-424	12.7	14.3	13
R-429	6.5	5.9	-
R-437	2.0	1.3	-
R-443	7.0	6.5	-
R-452	3.1	2.8	-
H-58	2.0	1.4	3
H-64	7.6	8.2	10
H-65	12.3	13.3	18
H-68	7.7	7.2	9
F-34	6.2	5.7	7
F-37	3.3	9.6	13
F-38	3.2	2.1	5

Six colorimetric kits and 1,500 analysis packets were delivered to the Air Force for use in field tests designed and administered by the Materials Laboratory. The tests were successfully performed at Myrtle Beach and Luke Air Force Bases on A-10 and F-15 aircraft. Most of the data obtained from monitoring these aircraft were in the concentration range of 0 to 5 ppm iron. However, there was one case where an engine experienced abnormal bearing wear. The CIK picked up this abnormality at the same time as the atomic emission instrument and earlier than the atomic absorption instrument. Detailed results are presented in a technical report (AFWAL-TR-80-4022) prepared by the Materials Laboratory.

The six Colorimetric Iron Kits used in the Air Force field test described above were refurbished and 2,000 additional analysis packets were prepared for testing by the Air Force in Europe. This test is currently in progress, and initial response to the training sessions was very favorable.

In conclusion, the Colorimetric Iron Kit provides a simple, on-the-spot test for iron, a major wear metal in jet engine lubricating oil. The CIK has been packaged so it is portable, safe, and easy-to-use (can be used by non-technical personnel). Some major characteristics of the portable kit are:

(1) Rapid - single analyses requires ∿8 minutes; two analyses require ∿12 minutes.

(2) Accurate - results comparable to atomic absorption data.

(3) Precise - repetitive analysis of used oil showed good precision.

(4) Portable - packaged in a 23.5 x 10 x 8.5 inch carrying case weighing 25 pounds.

(5) Inexpensive - lower cost than current AF-OAP instrumentation.

The Colorimetric Iron Kit provides a viable aid to the AF-OAP program. The kit is capable of providing rapid analyses in situations where sending a sample to a AF-OAP laboratory is impractical or would cause delays in aircraft mission performance.

FERROGRAPHY STANDARDIZATION

Peter B. Senholzi
Manager, Applications Engineering
Mechanical Technology Incorporated
Annapolis, Maryland 21401

Abstract: Wear particle technology is a recent development in the equipment wear field. This technology is based on the analysis of wear debris as a nondestructive reflection of the surface wear condition of the respective monitored wear process. This monitoring approach can be applied to everything from simple wear testing to sophisticated multi-component wear systems. Wear particle analysis technology is rapidly establishing itself as a valuable tool in both the wear prevention and wear control arenas.

Ferrographic analysis is a relatively new approach to the analysis of wear debris. Until recently, this technique has been utilized as a research tool in a limited number of laboratory facilities. However, as a result of initial successful utilization, ferrographic technology is receiving ever increasing interest. This increasing interest level has raised serious questions with respect to standardization and repeatability.

This paper describes an effort to quantify and apportion analytical ferrography repeatability/nonrepeatability. Under a program sponsored by the Office of Naval Research, four leading laboratories contributed controlled ferrographic analysis data. This data has been analyzed and the resulting repeatability/nonrepeatability assessed with respect to analysis variables.

Key words: Diagnostics; Health monitoring; Wear debris analysis; Ferrography; Wear; Tribology.

Introduction: Wear particle technology is a relatively recent development in the equipment wear field. This technology is based on the analysis of wear debris as a nondestructive reflection of the surface wear condition of the respective monitored wear process. This monitoring approach can be applied to everything from simple wear testing to sophisticated multi-component wear systems. Wear particle analysis technology is rapidly establishing itself as a valuable tool in both the wear prevention and wear control arenas. In order to fully realize the potential of wear particle analysis technology, additional research efforts must be implemented in order to enhance and expand the technology.

Ferrographic analysis is a relatively new approach to the analysis of wear debris. Until recently, this technique has been utilized as a research tool in a limited number of laboratory facilities. However, as a result of initial successful utilization, ferrographic technology is receiving increasing interest. This increasing interest level has raised serious questions with respect to standardization and repeatability.

This paper deals with the standardization of analytical ferrography. Primary emphasis will be directed at the quantification of ferrographic repeatability as well as the identification of respective significant contributing factors.

Background: Analytical ferrography is based on the magnetic precipitation and subsequent analysis of wear debris from a lubricant sample. The approach utilized involves passing a volume of lubricant over a glass substrate which is supported over a magnetic field. Permanent magnets are arranged in such a way as to create a varying field strength over the length of the substrate. This varying strength results in the precipitation of wear debris (magnetic and ferro-magnetic) in a distribution with respect to size over the substrate length (approximately 55 mm). Once rinsed and fixed to the substrate, this deposit serves as an excellent media for optical analysis of the wear particulates.

Ferrographic substrate deposit analysis involves the characterization of debris quantity, size distribution, elemental composition, and morphology. This total analysis effort involves both quantitative and qualitative assessments.

Quantitative assessments are derived for quantity and size distribution characterization utilizing a light reflected/light transmitted type densitometer. These assessments are registered by indicating the percentage of blocked area in a particular microscopic field of view. Readings are taken over the length of the substrate in order to characterize debris size distribution.

Elemental composition and morphological debris assessments are very qualitative in nature. They involve the manual characterization of debris deposits relying on observations conducted through an optical microscope.

This deposition and assessment process involves numerous variables. Such aspects as sample preparation, sample dilution, sample volume, sample viscosity, debris concentration, densitometer type, densitometer calibration, measurement approach, measurement indexing, and debris distribution, all affect ferrographic assessment results. These aspects can be generally categorized in three groups: technique/procedure; equipment; operator.

In the initial stages of ferrographic analysis, it was left up to each individual laboratory to address these analysis variables.

During the mid 1970's, a government sponsored international committee was established under The Technical Cooperative Program (TTCP) with the objective of fostering equipment health monitoring. A prime emphasis area of this committee was wear particle analysis and specifically ferrographic analysis. As part of this committee's efforts, lubricant samples were distributed among participating laboratories for wear debris analysis. Upon comparing sample analyses, it became apparent that slide variations existed between laboratory results. Further investigations revealed that at least a portion of this variation was due to individually developed/tailored ferrographic procedures. No variation apportionment could be made, however, between procedure, operator, and equipment. Thus, a severe standardization and repeatability problem was identified. This problem was intensified by the fact that ferrography was being applied by an ever increasing number of organizations in a variety of applications.

As a first step in attacking the problems of analytical ferrographic standardization, the Navy under an Office of Naval Research program proceeded to generate a preliminary detailed ferrographic procedure. Due to procedural controversies, dual procedural approaches were included for density lighting technique and density reading indexing approaches.

In order to verify this procedure, clarify controversial dual approaches, quantify repeatability, and identify respective significant contributing factors, two "round robin" sample analysis exercises were established between several major wear particle analysis facilities.

Standardization Program: As mentioned above, in order to verify the preliminary Navy Analytical Ferrographic Standardized Procedure, a joint program was developed and supported by several leading wear debris laboratories. A two phase "round robin" approach was instituted. Each phase consisted of the analysis of fluid samples as well as the analysis of premade ferrograph slides. This analysis was limited to analytical ferrography and did not include either direct reading or in-line ferrographic techniques.

Primary analysis variables addressed under this "round robin" exercise were procedure, equipment, and operator/location. Secondary addressed variables include: fluid type; debris concentration; debris size distribution; ferroscope type; ferrogram slide location; microscope lighting approach; and slide indexing approach. Round robin test design incorporated both primary and secondary variable treatment.

Statistical Approach: Respective ferrographic analysis data was submitted to a central location from each participating laboratory for each round robin phase. This data consisted of sets of density readings for each sample/slide, indexed with respect to ferrogram slide location. Supporting information for each set was also submitted which included such items as volume of fluid analyzed, dilution ratio, lighting approach, indexing approach, operator, and sample number. Statistical analyses were performed on these data sets in order to determine repeatability as

well as apportion nonrepeatability among the competing significant variables.

A four facet statistical format was applied to this data base. These four facets included data plots (slide position versus normalized density), analysis of variance, coefficient of variation analysis, and a graphical regression analysis. Examples of these four treatments are presented in Figure 1 through 4 respectively.

Expected outputs of this multifaceted statistical approach are summarized as follows:

- Data Plots
  - Trending Analysis
  - Scatter Comparison
  - Quantitative Comparisons
- Analysis of Variance
  - Variable Significance
- Coefficient of Variation Analysis
  - Repeatability Assessment
  - Repeatability Apportionment
- Graphical Regression Analysis
  - Bias
  - Discrimination
  - Quantitative Comparisons
  - Scatter
  - Trending Analysis

Results and Conclusions: Based on the statistical analysis as described above, the following results and conclusions have been generated. These results and conclusions are presented with respect to the primary and secondary analysis variables as covered earlier in this paper.

1. Lighting Technique: Both transmitted and reflected lighting approaches were considered with respect to analytical ferrography density measurements.

   A. Mean reflected density reading is higher than transmitted.
   B. Trends the same.
   C. Standard deviation the same.
   D. Coefficient of variation the same.
   E. Standardize on reflected approach.

2. Indexing Technique: Both a fixed density reading slide indexing approach (conventional) and a floating slide indexing approach (new method) were considered.

   A. Mean conventional density reading is the same as the new method.
   B. Trends the same.
   C. Standard deviation the same.
   D. Coefficient of variation the same.
   E. Standardize on conventional approach.

3. Equipment: Both Reichert and Olympus Ferroscopes were considered under this round robin effort.

A. Mean Reichert equipment density reading is the same as the Olympus.
B. Trends the same.
C. Standard deviation the same.
D. Coefficient of variation the same.
E. Minimal equipment effect on variation.

4. Slide Position: Repeatability with respect to the indexed location on the ferrogram was considered. Debris size is a function of this slide location.

   A. Minimal effect on variation.

5. Sample Type: Hydraulic fluid, mineral oil, and synthetic lubricant samples were considered.

   A. Minimal effect on repeatability.
   B. Hydraulic samples consistently higher variation.

6. Sample Debris Concentration: Light, medium, and heavy debris sample concentrations were considered.

   A. Light and heavy concentrations have most effect on repeatability/variation.

7. Intra-Laboratory: Repeatability within each laboratory was considered.

   A. Trends agree.
   B. Good repeatability

	Phase I Stage I	Phase II Stage I	Phase II Stage II
Mean COV	19%	5%	4%

   C. Procedure improved intra-laboratory variation.

8. Inter-Laboratory: Repeatability between all participating laboratories was considered.

   A. Trends agree.
   B. Poor repeatability

	Phase I Stage I	Phase I Stage II	Phase II Stage I	Phase II Stage II
Mean COV	50%	57%	37%	39%
C. Poor Discrimination				
Mean Discrimination	.91	1.5	.84	2.3

   D. Inconsistent inter-laboratory bias.
   E. Procedure has little effect on inter-laboratory variation.
   F. The prime source of inter-laboratory variation appears to be the ferroscope densitometer as opposed to either the operator or the sample procedure variables.

Summary: The results of this analysis have served to indicate that the preliminary Navy Standardized Ferrography Procedure has served to greatly improve the repeatability of analytical ferrographic analysis within an individual laboratory. However, repeatability between laboratories remains poor due to an equipment problem with the ferroscope densitometer. This problem could be addressed by the development of an effective densitometer calibration standard.

These results should not be construed as an effectiveness criticsm of either ferrographic analysis or wear debris analysis technology. Both of these interrelated technical fields have proven their effectiveness in both the maintenance and research communities.

The Navy Analytical Ferrography Standardized Procedure resulting from this effort will be published by the Office of Naval Research in the near future.

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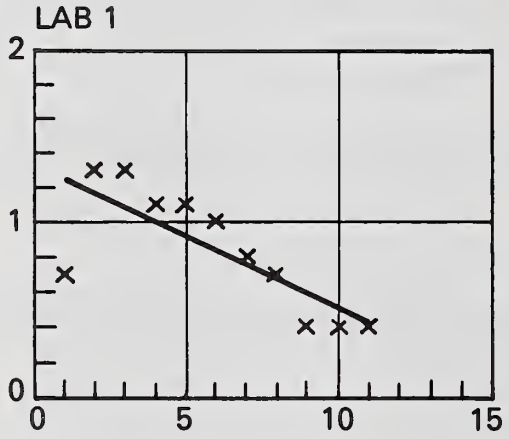
FIGURE 1

DATA PLOTS



MTI
PH887

FERROGRAPHY DATA

DENSITY VS SLIDE POSITION
LAB 1 SYNTHETIC
LIGHT
TRANSMITTED
NEW METHOD

$Y = -0.081\ X + 1.322$

YBAR = 0.836 SY = 0.347
SYX = 0.232 R = 0.743

Y	=	LEAST SQUARED EQUATION
YBAR	=	AVERAGE DENSITY READING
SY	=	STANDARD DEVIATION
SYX	=	STANDARD ERROR OF ESTIMATE
R	=	CORRELATION COEFFICIENT

FIGURE 2

ANALYSIS OF VARIANCE
FERROGRAPHY DATA

SOURCE OF VARIATION	SUM OF SQUARES SS	DEGREES OF FREEDOM DF	MEAN SQUARE MS/DF	MEAN-SQUARE RATIO MSR MS/MSRESID	F VALUE 90 PERCENT CONFIDENCE	CONCLUSION
TYPE OF OIL	2.	0.7970E+05	0.3985E+05	0.1093E+05	2.30	SIGNIFICANTLY EFFECTS DENSITY
CONCENTRATION	2.	0.2215E+05	0.1107E+05	0.3038E+04	2.30	SIGNIFICANTLY EFFECTS DENSITY
LABORATORY	4.	0.1592E+05	0.3980E+04	0.1092E+04	1.94	SIGNIFICANTLY EFFECTS DENSITY
LIGHTING	1.	0.5269E+03	0.5269E+03	0.1445E+03	2.71	SIGNIFICANTLY EFFECTS DENSITY
METHOD	1.	0.1838E+03	0.1838E+03	0.5041E+02	2.71	SIGNIFICANTLY EFFECTS DENSITY
SLIDE POSITION	10.	0.7250E+02	0.7250E+01	0.1989E+01	1.60	SIGNIFICANTLY EFFECTS DENSITY

FIGURE 3

COEFFICIENTS OF VARIATION ANALYSIS
SAMPLE DISTRIBUTIONS & LABORATORIES

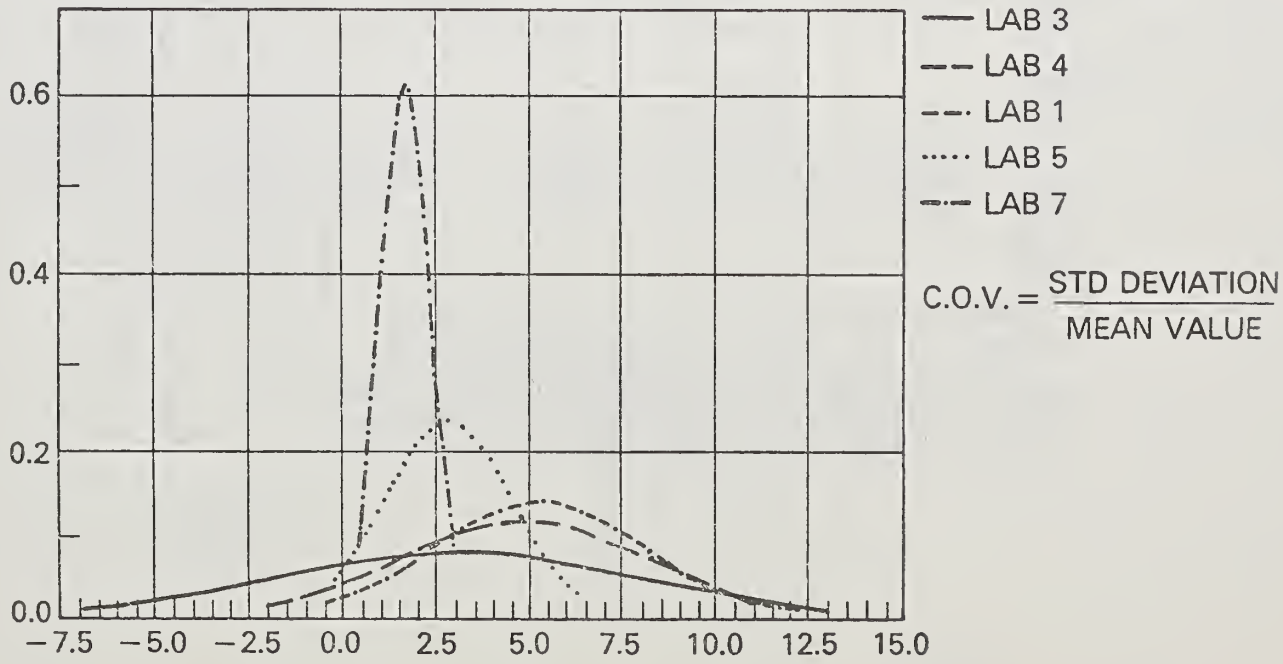
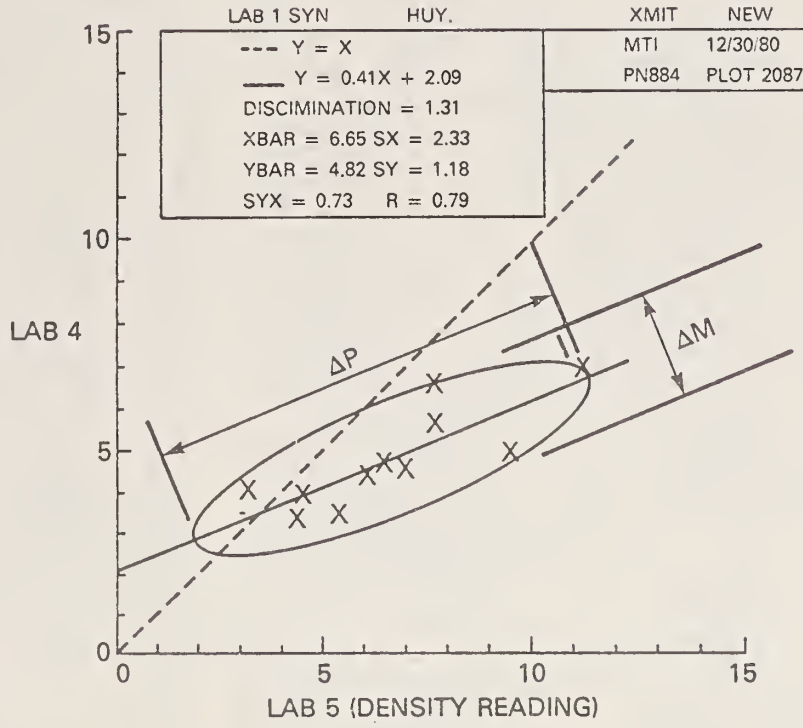


FIGURE 4

GRAPHICAL REGRESSION ANALYSIS



Y = LEAST SQUARE EQUATION

$$\text{DISCRIMINATION} = \frac{\Delta P}{\Delta M} = \frac{\text{VARIATION OF SAMPLE}}{\text{VARIATION OF PRECISION}}$$

XBAR = MEAN X DENSITY READING

SX = STANDARD DEVIATION OF X

YBAR = MEAN Y DENSITY READING

SY = STANDARD DEVIATION OF Y

SYX = STANDARD ERROR OF ESTIMATE

R = CORRELATION COEFFICIENT

A CONTINUOUS CORROSIVITY MONITORING DEVICE FOR THE MARINE ENVIRONMENTS

V. Agarwala
Naval Air Development Center
Warminster, Pennsylvania 18974

INTRODUCTION

Currently the assessment of corrosivity of an environment is made on the projected figures obtained on a cumulative basis from outdoor, longterm exposure tests. Tests such as salt fog, total or alternate immersion, are primarily designed from such projections to produce an accelerated laboratory test environment. Although these test methods have been quite successful in evaluating various materials, they are too often indiscriminately used. In situations where rapid weather changes control the nature of the environment or the locations are inaccessible, a true evaluation of the corrosivity of the environment is not possible. Any extrapolation of the results obtained from laboratory tests may be inaccurate at best, and deceptive, at worst.

The corrosion problems of naval aircraft are of a very severe and varied nature. In particular, sulfur from the carrier stack gases combined with sea spray provides a uniquely hostile environment (reference (a)). The aggressive naval aircraft carrier and marine environments not only undermine the structural integrity of the aircraft but also affect the navigational and communication systems as well. Inaccessible and critical functional areas of aircraft are very sensitive to even the slightest corrosion damage. An assessment of corrosion problems in such systems is almost impossible through the conventional corrosion tests. Corrosion of avionics, gear and gear housings, bearings and wing flaps etc. are well documented failures. In addition, the present trend to miniaturization and large scale integration of computer hardware in aircraft will even further increase their susceptibility to corrosion. Therefore, it is important that an assessment of the actual corrosivity of the environment be made before any laboratory testing procedure can be developed to simulate the environment.

In the present work a probe has been developed using well known techniques, (references (b) - (g)) which can monitor the corrosivity of the environment on a continuous basis and also can be placed in areas which are otherwise inaccessible. This probe is a series of electrochemical galvanic cells comprised of plates of two different metals such as aluminum and steel or steel and copper sandwiched together alternately separated by an electrical insulator and encapsulated in epoxy. When short circuited through an external electronic circuit of a zero-resistance ammeter, the condensed

moisture and the pollutants in the environment create an electrolyte (thin liquid film) on the surface of these plates which completes the circuit and develops a galvanic potential between the two. The magnitude of this cell current gives a measure of the corrosivity of the condensed film (the environment). The concepts of this technique were originally investigated by Sereda (reference (b)) who used platinum and zinc as the galvanic couple to measure the time of wetness during atmospheric exposure. Sereda's time of wetness measuring technique was arbitrarily based on a potential of 0.2V (a voltage drop across a 10M Ω resistor) as a timer was started when the potential drop exceeded 0.2V. Sereda chose this as a reference voltage developed by the Pt/Zn couple when exposed to an environment which contained 85% R.H. Tomashov and co-workers (reference (c)) independently utilized a similar approach and developed closely spaced galvanic cells for monitoring time of wetness of panels exposed to a high humidity environment. Later Kucera and Mattsson (reference (d)) modified this technique and the principles used earlier by Sereda and Tomashov to develop galvanic cells of copper and steel and suggested that they can be used to monitor atmospheric corrosion rates. Lauer and Mansfeld (reference (f)) and Mansfeld and Kenkel (reference (g)) further explored Kucera and Mattsson's suggestions and designed several galvanic couples made up from copper, steel, aluminum and zinc metals. More recently, Mansfeld (reference (h)) made a study of the effect of weather conditions and correlated the output of the couples with the corrosion rate. In the present work a study has been made to develop a wider use of this technique for specifically measuring the severity of the marine weather and the pollutants of the naval environment on corrosion behavior of steels and aluminum alloys.

EXPERIMENTAL DETAILS

PROBE DESIGN AND INSTRUMENTATION

The design of the probe was based on the approach used by earlier investigators (references (e) - (g)). Three galvanic couples, copper-steel, copper-aluminum and steel-aluminum were made from approximately 1 mm thick sheet metal stock of commercial purity. "Virgin" teflon of 0.75 mm thick was used as insulators. Ten pieces (5 x 2.5 x 0.1 cms) of each of the two dissimilar metals (one as a cathode and the other as an anode) were sandwiched together alternately and insulated by the teflon spacers. Two holes were drilled through this assembly for inserting nylon bolts to hold it together. All similar metal pieces (e.g., copper to copper or steel to steel) were short-circuited by thin electrical conductors and ended with two terminals, one for the cathode (e.g., copper) and the other for the anode (e.g., steel). The whole array of these plates was then thinly coated with stop off lacquer on the sides and potted in epoxy resin leaving only one long edge surface and the two wire terminals exposed. The potted assemblies were then sufficiently cured at room temperature before the exposed edge of the probe was surface ground and polished to

a 600 grit finish. The total exposed area of the probe was approxiately 5 cm^2 for each metal.

The galvanic cell current output from the probe was recorded on a periodic basis (short intervals) using the electronic devices such as a zero resistance ammeter (Z.R.A.), an anlog to digital converter; i.e., a digital panel meter (DPM) of very high impedance and a data logger. The schematic of the set up is shown in Figure 1. The ZRA was put together by using a potentiostat (Aardvark Model PEC-1) in which the voltage between the working (W) and reference (R) terminals was set to zero. A standard resistance box was connected between the reference (R) and counter (C) terminals for converting the galvanic current, I_g, into a potential drop for amplification and recording purposes. The digital data logging system used was a commercially available instrument from Precision Digital (Model 1040). The data logger was programmed to record probe output every 10 minutes during exposure. The choice of digital recording instruments eliminated the use of a log converter in this study as current variations of up to three orders of magnitude could be conveniently recorded without changing the resistance between (R) and (C). A 10KΩ resistor was adequate to give a current range of luA to lmA in naval environments.

ELECTROCHEMICAL CONCEPTS

The principles involved in the use of this corrosivity monitoring probe are those of corrosion of galvanically coupled metals. The driving force in the galvanic corrosion is the difference in electrode potentials between two dissimilar metals where the more active metal becomes the anode and the other the cathode. Usually the cathode or cathodic metal corrodes very little or not at all and corrosion of the anode or anodic metal is increased significantly. In other words, both metals are polarized so that each corrodes at a new rate. The extent of this polarization potential, η , of both the anodic and cathodic metals determines the magnitude of galvanic current flowing between two disimilar metals and is expressed by the Stern-Geary equation

$$I_g = I_{corr} \left[(10)^{\Delta\eta/\beta_a} - (10)^{-\Delta\eta/\beta_c} \right] \qquad (1)$$

After a series expansion and neglecting the higher terms assuming $\frac{\Delta\eta}{\beta_a}$ and $\frac{\Delta\eta}{\beta_c}$ being small, the equation (1) can be written as

$$I_g = I_{corr} \times 2.3\Delta\eta \left[\frac{1}{\beta_c} + \frac{1}{\beta_a} \right] \qquad (2)$$

where β_c and β_a are the Tafel slopes of the cathodic and anodic polarization respectively (reference (i)). However, when applied to

corrosion reactions in which the cathodic (reduction) reaction is under diffusion control (i.e., at the limiting current) and the IR drop is significant as one would expect in the atmospheric corrosion phenomena, the situation is equivalent to a large or infinite value of β_c in equation (2).

Hence, the equation (2) can be simplified as

$$I_g = I_{corr} \times 2.3 \left(\frac{\Delta\eta}{\beta_a}\right) \qquad (3)$$

But, for a particular couple at some steady state, the polarization potential $\Delta\eta$ becomes a constant. Hence

$$I_g = \text{Constant} \times I_{corr} \qquad (4)$$

i.e., the galvanic current, I_g becomes the corrosion current of the anode. This relationship is also in agreement with Mansfield and Kenkel (reference g)). However, it is important to note that the corrosion current, I_{corr}, does depend upon the electrochemical nature of the cathodic metal as it alters the value of $\Delta\eta$ in equation (3). In this analysis it has been assumed that the cathodic metal behaves more like an oxygen depolarizer therefore it undergoes the least corrosion. The extent by which the polarization potential, $\Delta\eta$, shifts is primarily dependent upon three important environmental variables, temperature, relative humidity and corrosivity (i.e., nature of the environment such as presence of O_2, salts, acids and other gaseous and particulate matter). In other words, the output of a galvanic probe will be dependent upon these parameters. Experimentally the observed changes will be directly related to the corrosive nature of the environment.

The details of the mechanism of galvanic corrosion phenomena are described elsewhere (references (c), (g), (i), (j), and (k)). Probably the best explanation of how a galvanic couple behaves in a corroding system is offered by the mixed potential theory (reference (j)).

PROCEDURES

The experimental program to explore the applicability of the corrosion monitoring probes utilized two laboratory environments and one natural environment to achieve three different exposure conditions: (1) a continuous high humidity (near 100% R.H.) environment; (2) an accelerated laboratory corrosion test environment; and (3) an aircraft carrier. The galvanic probes used to study these environments were copper/steel, copper/aluminum and steel/aluminum. Both copper and aluminum were commercially pure metals and the steel used was an AISI

1040 grade. Use of the three different galvanic probes for testing was made to determine the effect to potential difference as the driving force on the galvanic current developed in various media and to determine the performance of one metal over another in so far as the corrosion of anodic metal was concerned.

Near 100% relative humidity in the test chamber was created by passing compressed air through two vessels containing deionized water one after another and by using gas bubblers (fritted glass tubes). The humidity and temperature of the chamber were monitored by a digital humidity and temperature measurement system manufactured by Thunder Scientific Corporation (Model HS-1CHDT-2R). In experiments where chloride and acid were introduced into the chamber, the air bubbling vessels contained 1% NaCl and 6M HCl solutions respectively, instead of deionized water. With this procedure approximately 0.2 gm/m^3 of NaCl and 4 gms/m^3 of HCl could be present at any time in the chamber. The galvanic current transient curves (dotted) shown in Figures 2-4 represent the results of these test conditions.

In the accelerated laboratory corrosion testing, a salt fog cabinet meeting the requirements of ASTM B117-73, Appendix I, was used. A 5% NaCl solution was sprayed into the chamber as a continuous mist to simulate nearly wet conditions as experienced on naval aircraft carriers. In the tests where SO_2 laden salt fog was required, SO_2 gas was introduced in the cabinet for one hour four times a day while salt fog was continuously sprayed. The details of this testing are described elsewhere (reference (1)). The probe exposure data obtained by this accelerated laboratory corrosion testing are shown as continuous curves of galvanic current transients in Figures 2-4.

In the aircraft carrier exposure tests, the probe was installed on a radar tower about 20 feet above the flight deck of the aircraft carrier, USS JOHN F. KENNEDY (reference (m)). The galvanic current measuring instruments were located in the radar room to isolate them from the flight deck. The sensitivity of the recording system was set low so that at high relative humidity ($>$ 85%), the output of the probe was low (1-2 microamps). This way the full scale range setting on the recording system could measure up to 500 microamps. The probe output was recorded for a period of eight months, from June 1978 to March 1979, during which the carrier was deployed to the Mediterranean. At the end of the mission, the current transient records were analyzed and condensed as shown in Figure 5. The probe used in this study was a steel/aluminum couple.

RESULTS AND DISCUSSION

The galvanic current-exposure time output for the three probes, copper/steel, copper/aluminum and steel/aluminum, evaluated here in various corrosive environments are shown in Figures 2, 3 and 4, respectively. It has been shown that after an initial surface

conditioning of the probes which may take 5-10 hours, the probe output tends to become steady and depending upon the environment present in the chamber, the galvanic currents take an orderly relative position on the scale of corrosivity. Generally, it was found that as the corrosivity of the environment was increased the galvanic current measured by the probes also increased in the same order. This order of corrosivity was independent of the metals used in the probe but differed in magnitude depending on the couple. A comparative evaluation of their performance in various environments has been summarized in Table I. On comparison it was noted that the steel/aluminum probe was a little less sensitive to environmental variables. However, when the environment was of a highly acidic nature as in the case of 100% R.H + HCl (cf. Table I and Figure 4), the steel/aluminum probe showed an order of magnitude increase when compared to copper/steel. The copper/aluminum probe also showed a correspondingly higher output in the acid environment. Here, the logical explanation lies in the behavior of aluminum which becomes very active at very low pH and high chloride ion concentrations. This was also confirmed by the fact that almost the same corrosion potentials were measured for these couples (copper/aluminum and steel/aluminum) when immersed in a 3.5% NaCl solution (cf. Table II). A review of the electrochemical data obtained for three metal systems shown in Table II also indicated that as compared to the corrosion potentials of the couples, the open circuit potentials of the uncoupled anodic metals do not change significantly. It can therefore be concluded that in galvanic coupling the cathodic metal is mostly polarized and the galvanic current measured is largely due to the corrosion of the anodic member of the couple only; concurrent results were also reported by Walker (reference (n)). Although these results refer to an immersed state, it is believed that similar electrochemical polarization occurs on thin electrolyte films (condensed environment on the probe surface) as well, except for some kinetic effects which originate due to concentration limiting diffusion parameters. An earlier study by the author (reference (o)) relates to these conclusions.

Based on the results obtained by the corrosivity monitoring probes as summarized in Table I, the environments can be arranged as follows in the order of increasing corrosivity:

$$\text{Moisture} < (\text{Moisture} + \text{Cl}) < (\text{Moisture} + SO_2)$$

$$< \text{Salt Spray} < (\text{Salt Spray} + SO_2) < (\text{Salt Spray} + SO_2 + \text{Soak})$$

The increase in corrosivity from one environment to the next was almost an order of magnitude with the exception of the one which contained HCl. Some parallel tests on panels exposed to these environments also exhibited similar behavior and confirmed the results as shown by the probe output.

The condensed data of the aircraft carrier exposure test (reference (m)) after replotting, as shown in Figure 5, exhibit several periods of high corrosion activity (currents). In the first 40 days the steel/aluminum probe showed very little corrosion activity (less than 5 μA) indicative of normal marine weather and similar to those obtained from the probe in 5% salt spray environment (cf. Table I). Between 40 to 160 days there appeared to be periods of wetness resembling the data obtained in salt spray and SO_2 test environment. However, in the last 100 days of deployment considerable corrosive activity was recorded with galvanic currents as high as 500μA at some instance. This correlates with the reports from carrier personnel that the weather in the first four months of deployment was generally mild, whereas that of the last four months was characterized by storms and high seas. It also correlates with corrosion rates exhibited by the aluminum alloys exposed on the carrier when inspected at four months and eight months. Exfoliation attack was slight at four months and severe after eight months exposure (reference (m)). High current peaks were indicative of extremely corrosive conditions such as those created in the laboratory by periods of high acidity, chloride, SO_2 and almost wet conditions. In addition, the deposition of particulate matter such as heavy metals, soot and grease on the surface of the probe may have further accelerated the corrosion effects significantly. A qualitative analysis (AES) of the smut deposited on the probe showed detectable amounts of Cu, Ni, Pd, Cr, Fe and Mn. It has been reported by LaQue (reference (p)) that the presence of heavy metals like copper in sea water can accelerate corrosion of aluminum significantly. The results shown by the copper/aluminum galvanic probe in the laboratory accelerated test (cf. Table I) seem to substantiate this conclusion.

The results obtained by the probe in the carrier exposure tests were indicative of the diversities of environment where the weather in question changed frequently from very wet and corrosive to almost normal or calm. It then raises a question whether the corrosivity monitoring probe was actually responding to such changes in the carrier environment. To affirm that, the galvanic probes were subjected to a cyclic accelerated environmental test. It was comprised of a 30 minute spray of synthetic sea water (ASTM D1141-75, Section 6) in the spray cabinet followed by a 30 minute flow of SO_2, gas (flow rate of 1 cc/min/ft^3 of cabinet volume) and all activity stopped for the next two hours (called the soak period). At the end of the soak period the cycle starts all over again and continues, repeating every three hours. The probe exposure data obtained from these tests are shown in Figure 6. The I_g vs. time curves demonstrate a good correlation with the changing nature (corrosivity) of the environment in the cabinet. The gap in the arrows in Figure 6 indicates that the peak corrosivity of the environment was repeated after approximately three hours which coincided well with the cyclic period regulated in the cabinet. The gap in the arrows in Figure 6 indicates that the peak corrosivity of the environment was repeated after approximately three hours which

coincided well with the cyclic period regulated in the cabinet. The variations in the time of occurrence of these peaks were probably the result of initial surface stabilization of the probe and the frequency with which the cabinet cover was open. In subsequent long exposure tests these variables were better regulated. It was noted (cf. Figure 6) that the steel/aluminum probe was not as sensitive to the environmental changes as the other two. In order to determine the behavior of this probe on a long term basis, this test was continued for a period of five days. The results obtained from the copper/steel probe were even more interesting. As shown in Figure 7, the I_g vs. exposure time curve is made up of maxima and minima of the corrosion currents which were consistently repeated after every three hours and became very reproducible as the exposure continued. The ascending part of the curve coincided with the time when SO_2 gas was flowing into the cabinet after salt spray had ceased. Thus, the peaks correspond to the point in time where the probe experienced the highest SO_2 concentration; i.e, maximum acidity and maximum wetness as the salt fog continues to remain in the chamber for at least 1/2 hour after its flow has stopped. The extrapolated dotted lines in the curve (cf. Figure 7) were drawn to make the corrections in the curve, because during those periods, the cabinet cover was opened for examination which probably allowed the environment to escape (change) and therefore affected the results. The steady state values of the maxima and minima varied from 100 to 300 A showing extremely high corrosive environmental changes. In Table I a comparative summary of the performance of various probes used in the cyclic test has been given. From the actual panel exposure testing it was observed that this synthetic sea salt + SO_2 + soak cycle environment was probably the most corrosive of all accelerated laboratory corrosion testing environments (cf. Table I) and the type of attack produced had the closest resemblance to that obtained in he carrier environment.

CONCLUSIONS

Based on the principles of galvanic action a corrosion monitoring probe has been developed and evaluated for its usefulness in measuring the severity of the environment quantitatively. A comparative study of three galvanic probes, copper/steel, copper/aluminum and steel/aluminum showed that the copper/steel probe was most responsive to most varieties of environments in terms of its corrosion sensitivity and reproducibility when used on a continuous basis. In a simulated accelerated cyclic corrosion test environment, the corrosion monitoring ability of the probe was found to be in agreement with the cyclic corrosive nature of the environment. The aircraft carrier exposure results obtained by the probe indicated a very high corrosion activity caused by the presence of high wetness, sea salt, SO_2 and deposition of particulate matter (most probably heavy metals).

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TABLE I. EFFECTS OF ENVIRONMENTAL VARIABLES ON PROBE OUTPUT

Environment	Probe Output, I_g, [a] μA		
	Copper/ Steel	Copper/ Aluminum	Steel/ Aluminum
100% R.H.	0.01	0.01	$<$0.01
100% R.H. + Cl^- [b]	0.1	0.5	0.01
100% R.H. + C-HCl [c]	28	260	220
100% R.H. + SO_2	1.5	3	0.5
5% NaCl Spray	7.5	8	1.5
5% NaCl Spray + SO_2	140	80	7
Syn, Sea Water + SO_2 + Soak (Cyclic Test)	120-300	80-200	15-30

a I_g values at steady-state after 20 hours of initial exposure.

b Cl^- in the test chamber carried by the air when purged through 1% NaCl solution.

c HCl in the test chamber carried by the air when purged through 6MHCl solution.

TABLE II. OPEN-CIRCUIT POTENTIALS ($E_{corr.}$) AND CORROSION RATES ($I_{corr.}$) AFTER 24 HOURS IN 3.5% NaCl SOLUTION (IMMERSED).

Material	[1] $E_{corr.}$, V (Vs SCE)	Galvanic Couple	[11] $E_{corr.}$, V Vs SCE	[a] $I_{corr.}$ A/cm^2
Aluminum (C.P.)	-0.730	Steel/Al	-0.740	12
AISI 1040 Steel	-0.610	Cu/Al	-0.720	30
Copper (C.P.)	-0.240	Cu/Steel	-0.680	20

[a] Corrosion rates refer to the anodic member of the couples only.

[1] [11] $E_{corr.}$ and $E_{corr.}$ refer to potentials of uncoupled anodes and cathodes, and galvanic couples after one hour immersion respectively.

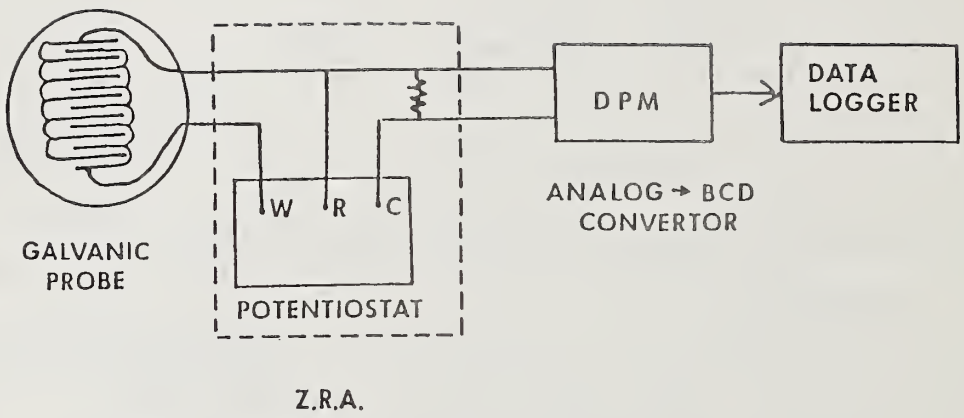

FIGURE 1. ENVIRONMENTAL CORROSIVITY MONITORING PROBE AND THE RELATED INSTRUMENTATION SCHEMATIC.

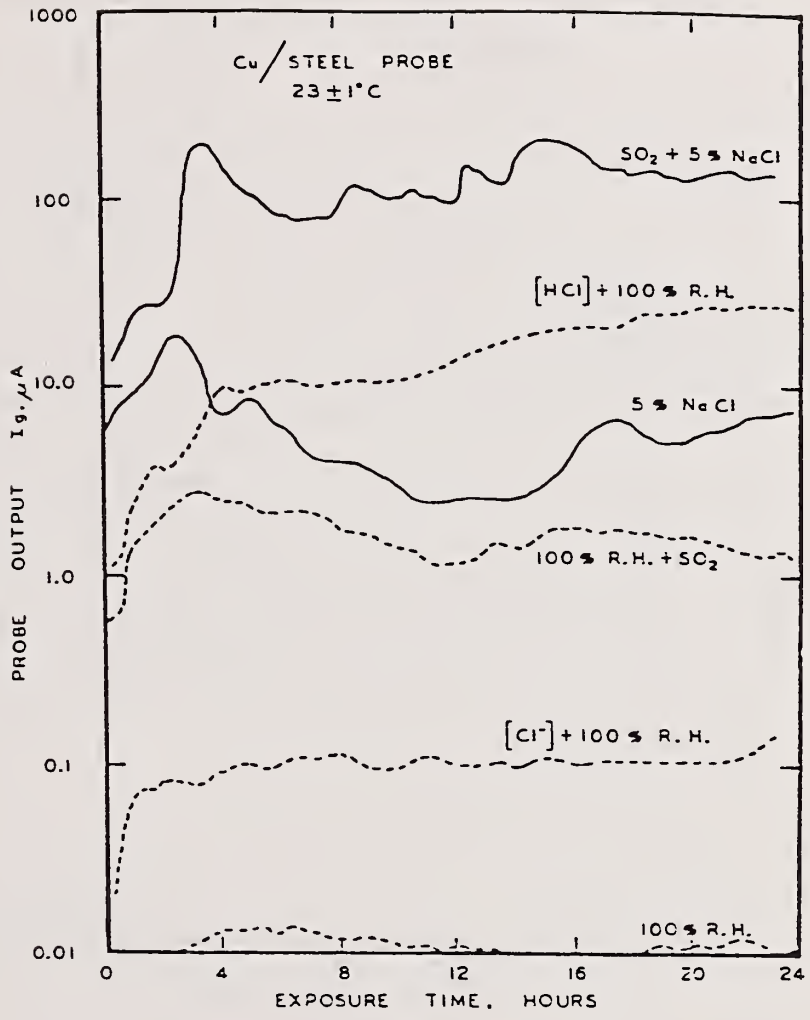

FIGURE 2. GALVANIC CURRENT TRANSIENTS OF COPPER/STEEL PROBE EXPOSED TO VARIOUS LABORATORY SIMULATED ENVIRONMENTS.

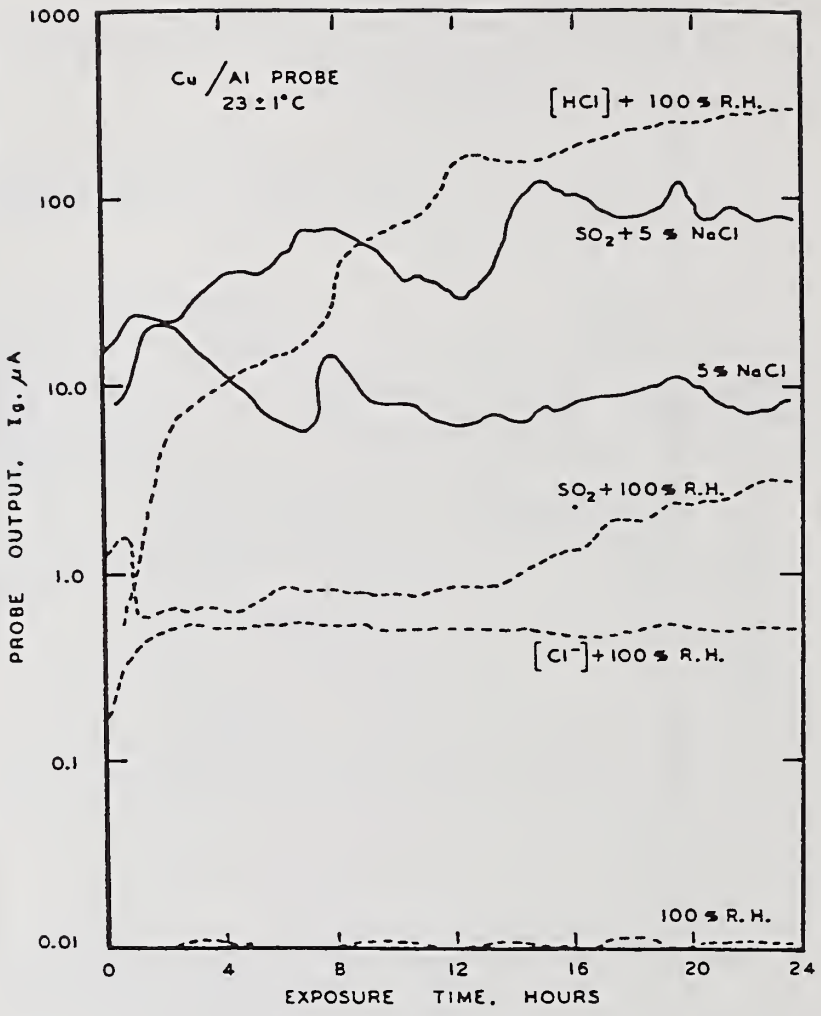

FIGURE 3. GALVANIC CURRENT TRANSIENTS OF COPPER/ALUMINUM PROBE EXPOSED TO VARIOUS LABORATORY SIMULATED ENVIRONMENTS.

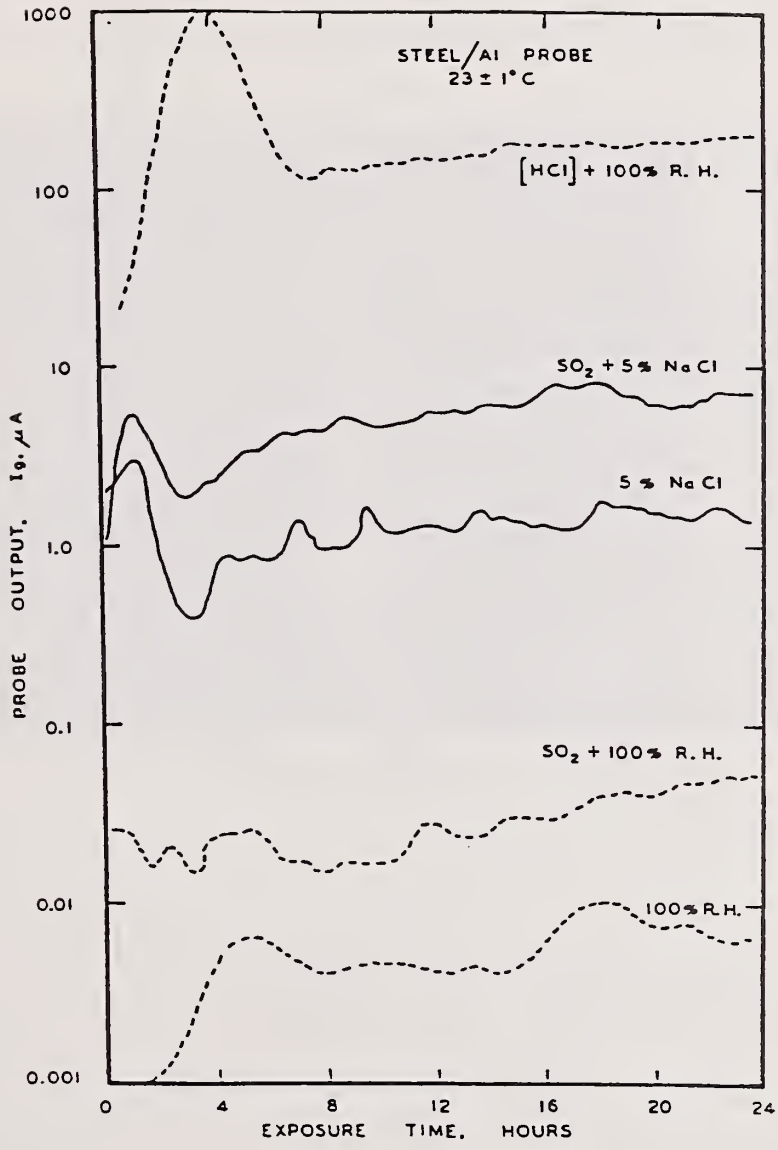

FIGURE 4. GALVANIC CURRENT TRANSIENTS OF STEEL/ALUMINUM PROBE EXPOSED TO VARIOUS LABORATORY SIMULATED ENVIRONMENTS.

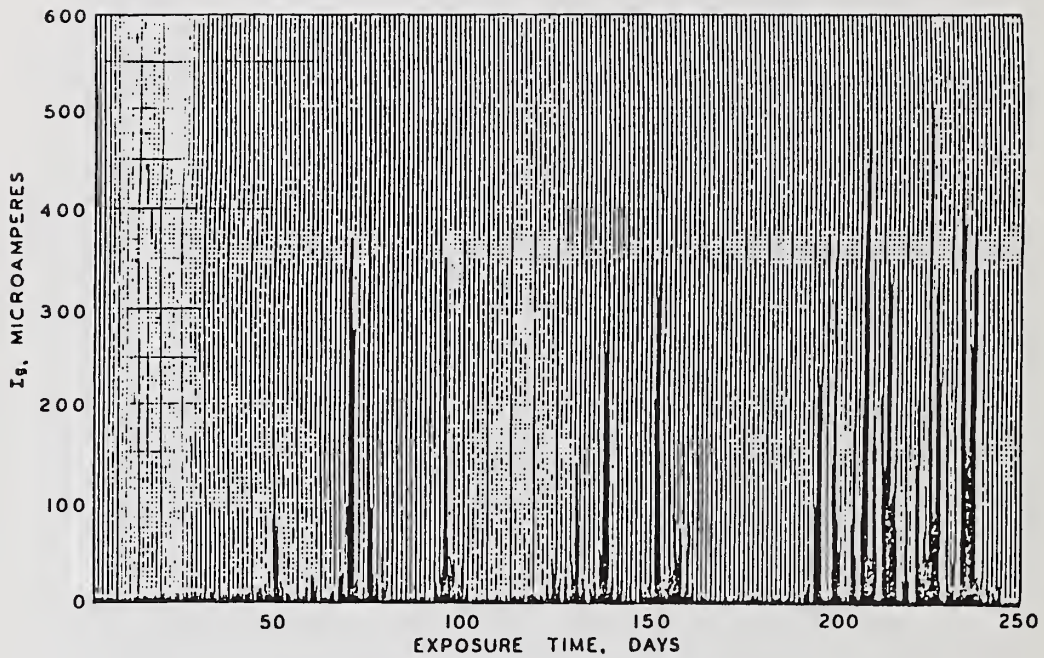

FIGURE 5. GALVANIC CURRENT TRANSIENTS OF STEEL/ALUMINUM PROBE EXPOSED TO AN AIRCRAFT CARRIER ENVIRONMENT.

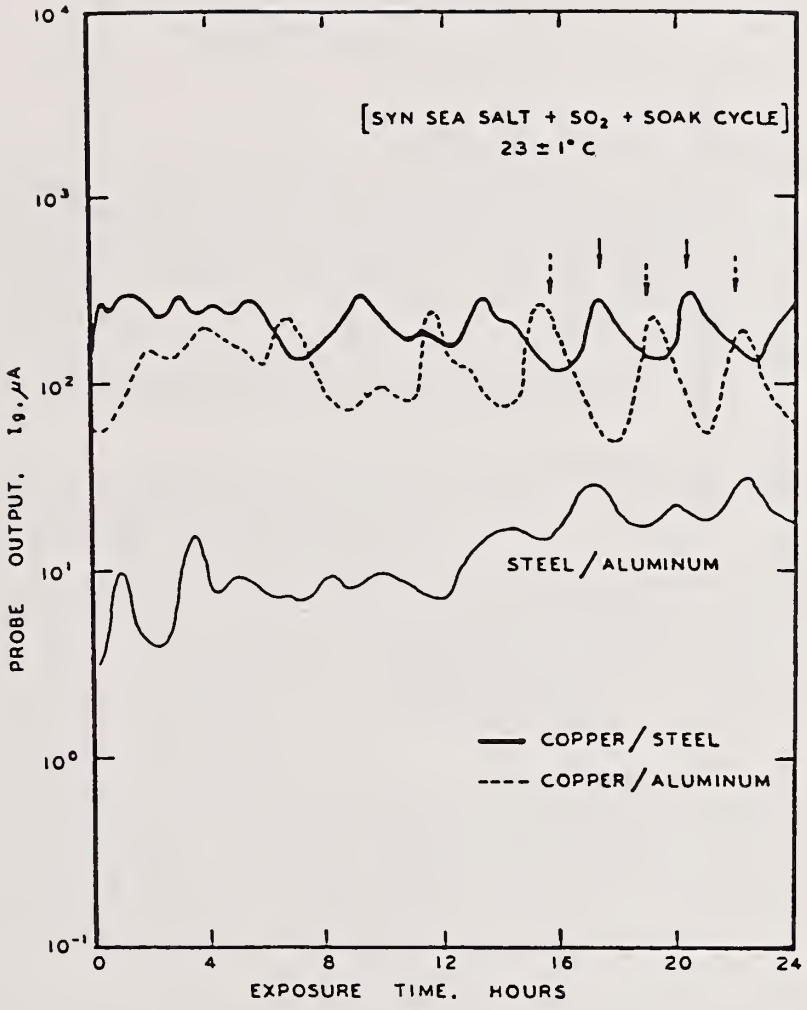

FIGURE 6. A SIMULATED CARRIER EXPOSURE TEST (SOAK CYCLE) DEMONSTRATING PROBE SENSITIVITY TO ENVIRONMENTAL CHANGES.

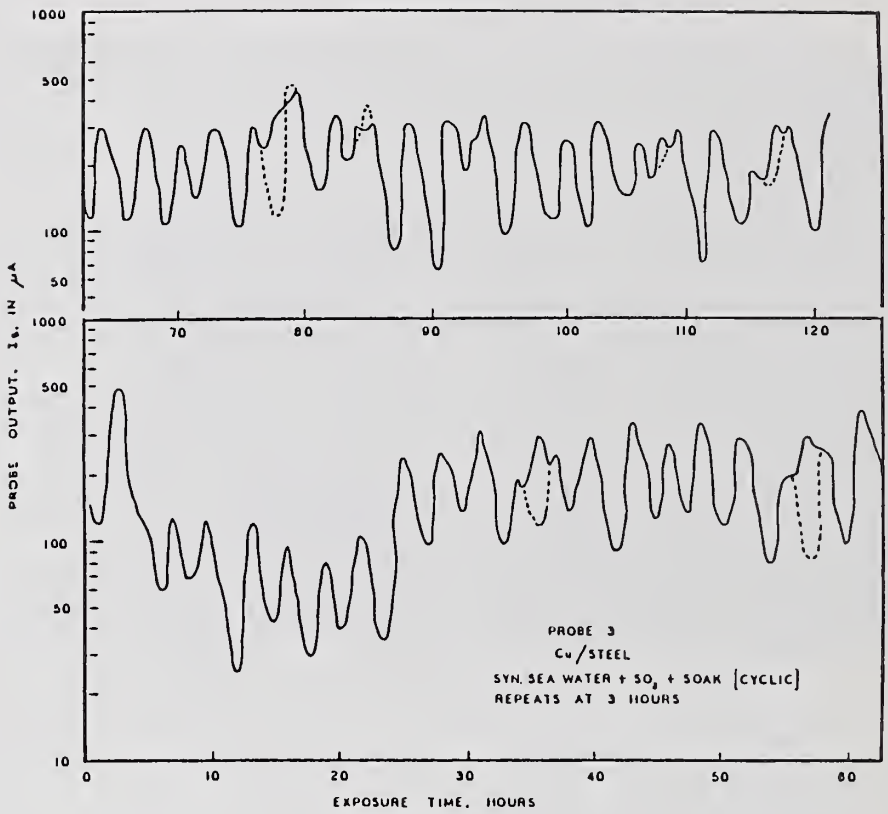

FIGURE 7. PERFORMANCE OF COPPER/STEEL PROBE IN AN ALTERNATING CORROSIVE ENVIRONMENT (SOAK CYCLE) OVER A LONG PERIOD OF EXPOSURE SHOWING THE CYCLIC NATURE OF THE ENVIRONMENTAL CORROSIVITY TEST.

IMPROVING MAINTENANCE MANPOWER UTILIZATION

Warren W. Lee
The Emerson Consultants, Inc.
30 Rockefeller Plaza
New York, New York 10112

Abstract: Managing the Maintenance function is extraordinarily difficult. Many factors contribute to this difficulty. Labor problems are complex because of craft lines. Efficiency is hard to achieve. It is difficult to schedule men and materials to jobs because of the constant interruption of emergencies. Overtime is commonly too high. Foreman usually are inadequately trained and receive little management support. The most difficult problem may be that of developing management understanding of the methods of maintenance cost control and an organization that desires and is able to control maintenance costs.

As a result of the many factors that make the management of maintenance difficult, some maintenance organizations handle maintenance on a breakdown basis rather than on a planned basis.

Breakdown maintenance is inefficient. With breakdown maintenance, foremen are trapped into becoming dispatchers. Craftsmen can't develop a work rhythm because they must go after tools and materials, wait on other crafts or wait on decisions. With breakdown maintenance, the Maintenance Department operates as a standby workforce.

Planned maintenance is more efficient. Crafts can be coordinated. Repair parts and materials can be provided. Production equipment availability can be arranged. Efficient ways of doing work can be developed. Bottlenecks can be anticipated and broken. When interruptions are avoided, craftsmen develop a work rhythm. Preventive maintenance is an important element of planned maintenance.

Before reviewing how to establish improved maintenance work procedures, we should review the problems normally associated with a breakdown maintenance organization so we will recognize what needs to be changed. Then we can discuss a program for change.

Work Practices and Procedures That Limit Maintenance Efficiency

Most of the practices that limit maintenance efficiency are susceptible to change by Management. When we look at maintenance operations, we find maintenance work is always impeded by bottlenecks. If these bottlenecks are removed, worker productivity improves. When we examine these bottlenecks, we find most result from omissions by foremen. If

Management takes care of these omissions, Maintenance worker productivity increases. Consider the following examples:

1. Maintenance crews commonly are slow about getting to work. Foremen who assign all work in the morning may take one and a half hours to get to the last assignment. The craftsman may not be told exactly what is wrong or what Management expects him to do. Instructions may be vague.

   The craftsman may have difficulty finding the job. He may not find the person who initiated the job, or find someone to tell him what is needed. We frequently find Maintenance workers starting late, (from one-half to one and one-half hours after the whistle) for reasons that are primarily Management's fault.

2. A second common problem is that the equipment is not ready to work on when the Maintenance people get to the job site. As a result, they are left standing around through no fault of the Maintenance crew.

3. Inadequate planning is a third problem area. A job may not have been investigated and planned. Assisting crafts may not have been coordinated. A pump mechanic may have to wait for the electrician or for a pipefitter to break connections or for a crane to lift the pump. If these craftsmen work for different foremen, there is no easy way for the primary craftsman to arrange this coordination, particularly if the needed man is busy on another job. The result is a crew standing around because management didn't coordinate the job.

4. Repair materials are a problem in some organizations. Spare parts may not be in stock. Tools and materials required for the job may not have been identified and delivered. That leaves it up to the craftsman to determine what is needed and find a way to get it.

   The plant may have no material delivery system, or no catalog from which to order stock materials. Or the catalog may be poor, completely unusable by a maintenance craftsman. Or a foreman's signature may be required to release materials. Then the crew must stop work and send one or more men to the storeroom. These constant interruptions make it difficult for craftsmen to develop a work rhythm. Again, the problem is not the worker's. It is Management's problem.

5. Increasing complexity of equipment is a problem. Machine speeds are increased. Sophisticated controls are added. Greater skills are needed to maintain this equipment. Few organizations have the training programs necessary to upgrade Maintenance employees' skill levels. A mechanic without adequate skills cannot be fully productive.

6. Inadequate preventive maintenance is a common problem. This not only results in excessive downtime of production equipment, but it increases the work that Maintenance must do. Instead of minor adjustments, Maintenance gets saddled with major repairs.

   When Maintenance doesn't perform preventive maintenance, the result is a great deal of breakdown maintenance. A high percentage of breakdown maintenance not only is inefficient, it forces Maintenance into the business of standby maintenance.

   There is no way to develop efficiency in a maintenance organization that is habituated to standby maintenance, to standing by to fix breakdowns. It is not enough just to repair equipment when it breaks down. Maintenance must avoid repair jobs where possible. This requires avoiding breakdowns through preventive maintenance procedures. It requires solving problems by design change, through changed operating procedures, or by retiring or replacing obsolete equipment that is responsible for excessive maintenance costs.

7. Supervisory practices are another area for problems. Foremen may spend little time at the job site. Their time may be taken up with meetings, with paperwork, or with planning. They frequently end up as dispatchers, depending on the men to find the job, and to decide what needs to be done.

   Some organizations support this Management philosophy. They take the attitude that the craftsman is paid to know the job, that foremen are a vestigial anomaly that will eventually disappear.

   I think it is significant that we find such crews never achieve the productivity of those with close and effective supervision.

8. Overtime causes many problems. Sometimes such problems are not recognized as symptoms of excessive overtime. It is fruitless to try to solve symptoms.

   The following are examples of problems arising from excessive overtime:

   - Supervisors develop a pay problem. Morale falls. Paying supervisors for overtime is not the answer.

   - It becomes difficult to find hourly employees who will accept promotion to supervisory positions.

   - Men get locked into higher standards of living. Then they must decide between taking care of their families and looking out for the company's interest. Frequently, they find that they must schedule overtime in order to maintain their social lives.

- o Absenteeism increases. Men become more prone to illness (possibly because they have more money).

- o Productivity and efficiency decrease. Studies indicate that two weeks may be the maximum period during which efficiency can be maintained under a heavy overtime schedule.

9. Modifications and alterations can account for major expenditures. When Management controls are inadequate, equipment may be modified without adequate analysis. Built-ins, cabinets and closets may spring up everywhere.

   A related problem is Management's failure to separate maintenance repair costs from other services such as janitors, power plant and utilities operation, unloading cars and trucks, providing relief operators and providing clean-up crews. When Management can't isolate all these costs, when they are lumped together as maintenance costs, there is no way to analyze operations. Under these conditions, effective control of maintenance costs is impossible.

10. The relationship between Maintenance and the user of maintenance services may need to be improved. The users may not feel constrained to help Maintenance in ways that lower maintenance costs. The user may feel no restraint on requests for service, no concern for giving Maintenance the time to do the planning and scheduling needed for efficient maintenance. If the additional cost of emergencies affects only the Maintenance budget, the user may not be concerned about Maintenance overtime or preventive maintenance.

11. Responsibilities for job priorities can present a problem. There is a basic conflict between Maintenance's need for time to plan and schedule work so that maintenance costs will be minimized and the user's desire for immediate repairs. Immediate repair requires a standby Maintenance crew. Organizations following this practice are bloated. Efficient maintenance requires time to plan and schedule.

    How can these conflicting needs be balanced?

    Management must recognize that this conflict exists and organize to handle it. They must develop an effective priority system. This is difficult. The user should have the right to say when repairs are needed. But good men dislike broken down equipment.

    There are two requirements for an effective solution of this conflict:

    - o A strong Maintenance Planning and Scheduling Organization.

    - o Dynamic use of job priority (set by the user).

Planning and Scheduling strives always to get time to plan. This conflicts with the user's legitimate desire for repairs to be made "NOW". But the structure is there to handle such conflicts. Most problems can be solved at a low level (planner and user). But the organization and procedures are present to carry problems as high as needed. It is the top man who must decide whether to increase staff or live with the potential delays.

Contractual Problems That Limit Maintenance Efficiency

We have been reviewing common causes of low productivity. As you can see, most are Management problems. Most can be eliminated by Management action. Most are simple to identify and not too difficult to cure.

Let's consider some more complex problems that interfere with Maintenance Management--problems that bottleneck maintenance productivity but are so difficult of solution that most managements ignore them.

1. First consider craft barriers. Do your labor agreements rigidly define the work a specific craft may do? The difference between organization is surprising. In some, mechanics regularly do most of the work related to a job. In others, several crafts may be required for a simple task. For example, a pipefitter and an electrician may be required to help an instrument man remove an instrument. The work may be well within the instrument mechanic's ability, but past practice requires three crafts.

   Consider how inefficient this becomes. If the job isn't planned, waiting time becomes excessive. If it is planned, planning and coordination costs become excessive, because the planner must communicate with several crafts. Between planner and foremen, they may waste more time than it takes to do the job.

   Who is responsible for preventing an increase in craft barriers? Who is responsible for developing a plan, for negotiating an "incidental work" agreement, and for enforcing the agreement after it is made?

2. Another difficult problem area is maintaining Management's rights under the contract. We expect foremen to operate effectively in the face of growing Union strength. Do we train them in the details of the contract? Do we consult with them before negotiations? Is it any wonder that foremen end up taking actions that Management subsequently decides not to support?

   After Management has failed to train their supervisors and then finds it undesirable to support their actions, we get an inevitable

result. The foremen decide to play it safe and minimize their exposure by "managing" as little as possible.

3. Another difficult problem is controlling entry into the Maintenance work force. Some organizations have no apprentice program, no series of examinations that a craftsman must pass. As a result, unsuitable people can get into Maintenance. Once in the Maintenance organization, there frequently is no way to get these people out and little way to upgrade them. In time, such practices will weaken the entire group.

A Program For Change - The Route To Efficient Maintenance

We have reviewed the problems that make Maintenance Management difficult, both the obvious problems that yield to direct action and the complex problems that are harder to solve. Our purpose has been to spotlight the problems that face Maintenance Management so that we can tailor our solutions to these problems. Here are the steps that we have found to be successful for accomplishing a turnabout of the Maintenance function:

First, identify your problems. Look for the obvious problems I've listed here. Determine their trends and evaluate their seriousness. Measure your productivity with work sampling. Reduce your findings to writing.

Second, develop a plan for change. Get the plan approved by Management. Schedule each step you will take and assign responsibility for each step.

The following actions are those we have found to be effective for identifying and removing those bottlenecks that limit the productivity of Maintenance organizations.

1. Develop a sound organization that recognizes the functions that must be accomplished and structures the organization for their accomplishment. Chief among these structures are separation of planning and work execution, proper relationship between Stores and Maintenance, proper relationship between the user and Maintenance, provision of needed Engineering functions and relating the work force to specific areas of large installations.

2. Establish effective procedures that make it easy to initiate, execute and control Maintenance work. Following are the procedures that we have found most effective:

   - Preplan the jobs so that needed materials may be identified and supplied and crafts and equipment may be coordinated.

- o Assign work the day before in order to avoid the morning start-up delays.

- o Assign more than one job so that the craftsman always knows where his next job will be. That way he does not need to stretch out the current assignment. He won't need to return to the shop for his next job and, if the foreman is absent, be forced to wait.

- o Get the foreman out on the job with the clearly identified goal of finding and eliminating the bottlenecks. He should understand that his goal is to help his men do the job efficiently, not "look down their collar."

- o Provide Materials Management that includes:

  - Effective stock control (expensive to establish, but profitable)

  - Good warehouse procedures

  - An adequate catalog so that Maintenance people can tell what material is available and can order it by telephone.

  - And last, a delivery system that will get material to the craftsman rather than requiring him to come after it.

- o Establish a priority system. The user should set priorities. The Maintenance Planner only negotiates priorities. However, he can approach the user this way: "I have this many people to schedule. Which jobs do you want tomorrow?"

  Most priorities are set at a low level (user versus planner). Some rise for Management consideration when the user can't accept delay. Management must decide between accepting such delays or providing extra staff.

- o Control facilities modifications and alterations. First line user supervisors should be able to authorize major repairs but only limited dollar alterations. Alterations should be approved by Engineering. Approvals should be monitored by Planning. The work order provides the control vehicle.

- o Establish work sampling. This is the most meaningful measure of the suitability of staffing level. Monitor other measures of Maintenance performance such as downtime, equipment failures, labor hours, overtime levels, and the like.

These are the principal procedures that usually need attention. Do not neglect the more difficult problems.

3. Establish overtime controls. Hold total overtime to a low level (10% maximum). Identify causes of overtime and the amount per cause. Apply effort where it is needed. Reduce emergencies. Schedule for week-ends. Minimize scheduled overtime.

4. Provide a work order system for Maintenance. The work order should be designed to accomplish the following functions:

   Requesting maintenance work

   Approving requests for maintenance work

   Planning the job

   Opening the computer cost collection account (for the Management Information System)

   Requisitioning material (in some cases)

   Reporting completion of the job

   It should provide for coding the following information as a minimum:

   Priority

   Production cost center

   Identification number of equipment being repaired

   Reason for undertaking modifications or new construction

   AFE, RFA, or project number if the work order is part of a larger job

   The expense classification for budgetary purposes

   The names of all authorities approving the request

   An estimate of labor, material and total dollars required to complete the job

   The reason the equipment failed or needed repair

5. Provide training as needed for all employees. Train the foremen and the craftsmen in the technical aspects and best methods of doing their jobs. Teach the foremen to understand the contract and to manage within the provisions of the contract. Make sure that second level Management discharges its responsibility to train the foremen to know what their jobs are and how to accomplish them.

As part of the training program, develop controls over entry into the Maintenance Department. Also develop an apprentice training program that will increase the craftsman's competence. This program should have the ability to reject trainees that aren't going to develop into suitable journeymen.

6. Establish a good Preventive Maintenance program. Preventive maintenance is more than a lubrication program, more than an inspection program. It includes the analysis of breakdowns and an attempt to prevent them. It includes review of equipment design and specifications to identify and avoid equipment known to perform poorly. It includes finding and eliminating operating procedures that are responsible for excessive maintenance in the organization.

7. Protect the rights of Management versus those of the Union. Pay close attention to the day-to-day problems that come up between foremen and the Union. Insure that the positions taken fairly reflect the contract. Be alert to prevent the Union nibbling away at Management rights by establishing adverse procedures that the Union can later claim as "past practice."

   Make sure that the foreman understands and exercises Management rights. Protect him from taking positions that Management may not be able to support and which may result in Management actions that destroy the confidence and authority of the foreman.

   Prepare for the periodic negotiation of a new contract. The Union, at national, regional and local levels, plans what they are going to take away from Management. They develop positions and strategies for the negotiating table. This is their business. They are professionals and spend full time at it.

   Management can't hope to negotiate effectively with the Union, to support its own position adequately, if two weeks before the negotiations the man selected to head up the Management team sits down and throws together a position paper. This is particularly true when his primary contact with line management occurs only at negotiating time, or if his contacts have been limited to periods when line management has gotten into difficulty. When the negotiator's contacts are thus limited, he loses confidence in line management to the extent that the two of them have difficulty forming an effective team.

8. Consider negotiating for a reduction in craft barriers. A first step within reach of most companies is an agreement for the principal craft to perform minor associated tasks or incidental work.

9. Provide a Management Information System if your operation is large (over 100 Maintenance people) or if your company has several large plants.

The Management Information System requires computerized work order accounting that communicates with payroll and labor distribution, with warehouse stock materials accounting, and with outside purchased materials accounting.

Such a Management Information System can help with the control and management of maintenance.

One Last Reminder

Keep in mind that it is the foreman and his team that gets maintenance work done. Planners don't do maintenance work. Neither does Management. It is the maintenance mechanic supported by his foreman that gets the job done.

Few foremen receive the management support they need and deserve.

Few craftsmen receive the support they need and have a right to expect.

Management needs to make some fundamental changes:

- Eliminate criticism as a mode of dealing with the foreman. He is the only one of the Management team who is working face to face with the worker. Criticism too often reflects Management's lack of understanding of his situation or Management's refusal to accept their responsibility for helping him become effective.

- Support the foreman. Support him with training in all the more obvious areas, but most important, keep the general foreman in the field showing him how to support his men, training him to find and break the bottlenecks that slow down the job.

- Support the craftsmen. Train them in craft skills and recognize and support their pride in these skills. Help them become master mechanics and maximize their opportunities for self-realization on the job.

- Recognize that it is Management's job, not merely to direct, but to train and support the general foremen.

APPENDIX

MECHANICAL FAILURES PREVENTION GROUP

Innovation for Maintenance Technology Improvements

33rd Meeting

April 21-23, 1981

Attendance List

Ricardo R. Ablaza
U.S. Dept. of Transportation
Federal Highway Admin., HDV-13
400 7th Street, SW
Washington, DC 20590

U.S. Agarwala
Naval Air Development Center
Code 606
Warminster, PA 18974

D.K. Anand
National Science Foundation
1800 G. Street NW
Washington, DC 20006

David F. Appleby
Royal Australian Air Force
Office of the Air Attache
Embassy of Australia
1601 Massachusetts Ave.
Washington, DC 20036

J. Ariano
Applied Technology Laboratory
Ft. Eustis, VA 23604

Yayesh Asmerom
Pennwalt Corporation
900 First Avenue
King of Prussia, PA 19406

Phil Badger
Consultant
Box 54
Washburn, IA 50706

M.K. Bernett
Naval Research Laboratory
Washington, DC 20375

Lou Bergan
Atacs Industries
1120 SW 16th Street
Renton, WA 98055

Philip Bloomfield
Pennwalt Corporation
900 First Avenue
King of Prussia, PA 19406

Paul H. Bowen
Westinghouse Electric Corp.
1310 Buleah Road
Pittsburg, PA 15235

A.P. Brackney
Monsanto Company
730 Worcester Street
Indian Orchard, MA 01151

Bobby Brown
Naval Air Systems Command
2624 10th Street, NE
Washington, DC 20018

Anthony J. Bukowski
Naval Air Propulsion Center
Parkway Avenue
Trenton, NJ 08628

Harry C. Burnett
National Bureau of Standards
Building 223, Room B-166
Washington, DC 20234

Charles E. Burns
Life Cycle Engineering, Inc.
615 Wesley Drive, Suite 212
Charleston, SC 29407

Andy Callahan
Endevco
Rancho Viejo Road
San Juan Capistrano, CA 92675

William M. Capece
General Technology
370 Paoli Avenue
Philadelphia, PA 19128

Nikolaos Caravasos
Boeing Vertol
P.O. Box 16858
Philadelphia, PA 19142

B.W. Christ
National Bureau of Standards
1605 Cryogenics Building
Boulder, CO 80303

Bryan D. Cleveland
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

John F. Clayton
Gulf Canada Research & Development
Sheridan Park
Ontario, Canada L5K1A8

Chester M. Dacres
Naval Surface Weapons Center
White Oak, MD 20910

Raymond J. Dallry
Ferrography (Loxboro Analytical)
78 Blanchard Road
Burlington, MA 08103

George DeLong
Resource Management Systems
1250 Sixth Avenue, Suite 300
San Diego, CA 92101

M.J. Devine
General Technology
2560 Prescott Road
Haverton, PA 19083

Stanley W. Doroff
Mechanical Technology, Inc.
2731 Prosperity Avenue
Fairfax, VA 22031

Walter D. Downing
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

J.G. Early
National Bureau of Standards
Materials Building, Room A-113
Washington, DC 20234

Charles Eby
Monsanto Research Corporation
1101 17th Street, NW
Washington, DC 20036

John R. Elliott
U.S. Army/MIT
125 Lowell Street, Apt. 409
Somerville, MA 02143

Francois Envent
ManTech International Corporation
2341 Jefferson Davis Highway
Arlington, VA 22202

Herb Evans
Pennsylvania Instrument
Spring City, PA 19475

J. Fay
Advanced Logistics Management, Inc.
1745 South Jefferson Davis Highway
Arlington, VA 22202

Maj-Britt K. Gabel
Wear Sciences
R.D. 7, Box 70, Gabel Road
Coatesville, PA 19320

Jerry H. Garant
U.S. Marine Corps.
M & L Division, Dev. Center
MCDEC
Quantico, VA 22134

Thomas J. Green, Jr.
SEMCO
Div. of Products Research &
Chemical Corporation
410 Jersey Avenue
Gloucester City, NJ 08030

Raymond Guyer
SKF Industries
1100 First Avenue
King of Prussia, PA 19406

Robert A. Hall
U.S. Army Applied Technology
Laboratory
Building 401
Fort Eustis, VA 23604

Robert E. Hartwell
RCA
P.O. Box 588
Burlington, MA 01803

H.R. Hegner
ManTech International Corporation
2341 Jefferson Davis Highway
Arlington, VA 22202

R. Curtis Heinen
Southwest Research Institute
P.O. Drawer 28501
6220 Culebra Road
San Antonio, TX 78284

William Hillan
Monsanto
1515 Nicholas Road
P.O. Box 8
Dayton, Ohio 45407

Don P. Hodge
U.S. Army
114 Meeks Drive
Aberdeen, MD 21001

Fred W. Hohn
RCA, Mail Stop 9-2
P.O. Box 588
Burlington, MA 01803

G.W. Holbrook
Dow Corning Corporation
Midland, MI 48640

R.R. Holden
Hughes Aircraft Company
Building 110, Mail Station 63
P.O. Box 90515
Los Angeles, CA 90009

Kenneith E. Homer
Optimal Systems, Inc.
P.O. Box 1182
Atlanta, GA 30301

Bradford W. Jameson
Monsanto-Bircham Bend Plant
190 Grochmal Avenue
Indian Orchard, MA 01151

Karl-Edward Johansson
Linkoping University
Linkoping Institute of Technology
Dept. of Mechanical Engineering
S-58183 Linkoping, Sweden

Joseph John
I.R.T.
7650 Convoy Court
P.O. Box 80817
San Diego, CA 92138

James M. Kelly
HQ, U. S. Marine Corps (Code LMM-3)
HQMC
Washington, DC 20380

A.J. Koury
Naval Air Systems Command
AIR-4114C
Washington, DC 20361

Robert Kincaid
Spectron Carbide, Inc.
Condominio Las Lomas No. 2
Cadparra Heights, PR 00921

J. King
Pennwalt Corporation
900 First Avenue
King of Prussia, PA 19406

George Kitchen
Bell Telephone Laboratories, Inc.
Murray Hill, NJ 07974

E.E. Klaus
The Pennsylvania State University
133 Chemical Engineering Building
University Park, PA 16802

Judi Komaki
Georgia Institute of Technology
Engineering Experiment Station
Atlanta, GA 30332

P.R. Langston
E. I. DuPont deNemours & Co., Inc.
Centre Road Building
Wilmington, DE 19898

Vincent J. Lanza
Metco Inc.
1101 Prospect Ave.
Westbury, NY 11590

Jorn Larsen-Basse
University of Hawaii
Department of Mechanical Eng.
2540 Dole Street
Honolulu, HI 96822

Richard S. Lee
JOAP-TSC (U.S. Army)
Building 780, NAS
Pensacola, FL 32508

W.M. Lee
The Emerson Consultants, Inc.
8806 Chippenham Parkway
Richmond, VA 23235

Rudolph Lenich
Caterpillar Tractor Company
100 NE Adams Street, AB6D
Peoria, IL 61629

H.T. Lootens
U.S. Army
Aberdeen Proving Ground, MD
21005

K. Ludema
University of Michigan
Department of Mechanical Eng.
Ann Arbor, MI 48109

Malte Lukas
Baird Corporation
125 Middlesex Turnpike
Bedford, MA 01730

P.B. MacPherson
Westland Helicopters, Ltd.
Yeovil
Somerset, England

H.P. Martin
Office of Naval Research
Code 470B
800 North Quincy Street
Arlington, VA 22217

Dick McLaughlin
RCA
P.O. Box 577
Burlington, MA 01778

Ronald E. Mead
USAF, AF Logistics Command
611 Pinewood Place
Beavercreek, OH 45430

Robert Mehrabian
National Bureau of Standards
Materials Building, Room B-266
Washington, DC 20234

William Menth
Metco Inc.
1101 Prospect Avenue
Westbury, NY 11590

Robert W. Messler, Jr.
Eutectic Corporation
40-40 172nd Street
Flushing, NY 11358

Victor Middlebrook
Transportation Systems
Consulting Corporation
P.O. Box 230
5 Stanford Street
Huntington Station, NY 11746

D.V. Minuti
Naval Air Development Center
Code 606
Warminster, PA 18974

Ray Misialek
NAVSSES
Philadelphia, PA 19112

Thomas P. Mortimer
Pratt & Whitney Aircraft
400 Main Street, EB 3S4
East Hartford, CT 06108

Thomas A. Nebel
Monsanto - Bircham Bend Plant
190 Grochmal Avenue
Indian Orchard, MA 01151

Bill Needelman
Pall Corporation
30 Sea Cliff Avenue
Glen Cove, NY 11592

Gerald A. Nowotarski
Rilsan Corporation
139 Harristown Road
Glen Rock, NJ 07452

John T. Oakley
Techplan Corporation
65 West Street Road
Warminster, PA 18974

Betty O'Keefe
Rilsan Corporation
139 Harristown Road
Glen Rock, NJ 07452

Daniel Pauze
U.S. Army Propulsion
Laboratory (AVRADCOM)
Lewis Research Center, MS 302-2
21000 Brookpark Road
Cleveland, OH 44135

Sal Pera
RCA - Government Systems Division
P.O. Box 588
Burlington, MA 08803

M. Peterson
Wear Sciences
925 Mallard Circle
Arnold, MD 21012

H.E. Pohlenz
Hughes Helicopters, Inc.
Centinela and Teale Street
Culver City, CA 90230

H. Porter
Advanced Logistics Management
Incorporated
1745 South Jefferson Davis Hwy.
Arlington, VA 22202

S.B. Poteate
Applied Technology Laboratory
Ft. Eustis, VA 23604

Robert Pond, Jr.
USNA
117 Glen Aryle
Baltimore, MD 21212

John P. Pruett
Kelly Air Force Base
SA-ALC/MMETS
Kelly, AFB, TX 78241

G.G. Quirk
Monsanto Company
730 Worcester Street
Indian Orchard, MA 01151

Raul A. Raudales
Industrias Ra
P.O. Box 230, Coma ya guela
Honduras, Central America

B.R. Reason
Cranfield Institute of Technology
Cranfield, Bedford MK43 OAL
United Kingdom

N.D. Rebuck
Naval Air Development Center
Code 6061
Warminster, PA 18974

Richard Rio
Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, NY 12110

Donald J. Rokos
Interlube, Inc.
205 W. Grand Avenue, Suite 125
Bensenville, IL 60106

Harry Rolka
Dow Corning Corporation
Mail Stop 10
Midland, MI 48640

A.W. Ruff
National Bureau of Standards
Materials Building, Room B266
Washington, DC 20234

S. Sarian
ReLuxtrol, Inc.
333 Victory Avenue
South San Francisco, CA 49080

R.L. Scharpf
Applied Technology Laboratory
Ft. Eustis, VA 23604

G.N.D. Seddon
University of Manchester
Simon Engineering Labs.
Oxford Road
Manchester M13 9PL
United Kingdom

Peter Senholzi
Mechanical Technology, Inc.
1656 Homewood Landing Road
Annapolis, MD 21401

J.P. Sharma
Indian Institute of Technology
Hauz Khos
New Delhi, India 110029

Jon A. Shelton
USCPSC
5401 Westbard Avenue
Bethesda, MD 20207

T.R. Shives
National Bureau of Standards
Materials Building, Room A113
Washington, DC 20234

William Skewis
Eagle Technology Inc.
2300 S. 9th Street
Arlington, VA 22204

Richard M. Slayton
Pratt & Whitney Aircraft
71 Saginaw Street
South Windsor, CT 06074

Richard Smith
Shaker Research
Northway 10 Executive Park
Ballston Lake, NY 12019

J.E. Stern
Trident Engineering Associates
1507 Amherst Road
Hyattsville, MD 20783

William C. Stitzel
Armco, Inc.
703 Curtis Street
Middletown, OH 45043

C. Trainer
Interlube Systems
Plymouth, England

Steven VanHoff
Puget Sound Naval Ship Yard
Bremerton, VA 98314

James L. Vannest
Fafnir Bearing Division
Textron, Inc.
37 Booth Street
New Britain, CT 06050

John F. Wagner
Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, NY 12110

Jeff Warren
NSWC - White Oak (Navy)
Code R34
White Oak, MD 20910

W.A. Willard
National Bureau of Standards
Materials Building, Room A-113
Washington, DC 20234

E. John Wootten
Bruel & Kjaer Instruments, Inc.
185 Forest Street
Marlborough, MA 01752

G. Allan Whittaker
Honeywell, Inc.
2600 Ridgway Parkway
Minneapolis, MN 55413

Anthony Wu
Science Division, C.C.N.A.A.
4301 Connecticut Avenue, NW
Suite 132
Washington, DC 20008

Donald J. Yanusko
Pennsylvania Instrument
Service Corporation
R.D. 1, Box 231
Spring City, PA 19475

Ronald W. Yound
Rockwell International
Rocketdyne Division
6633 Canoga Avenue
Canoga Park, CA 91304

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3. Proceedings of Meeting No. 10 . . . . . AD 721 912
   "Vibration Analysis Systems"
   January 21-22, 1970

4. Proceedings of Meeting No. 11 . . . . . AD 724 475
   "Failure Mechanisms: Fatigue"
   April 7-8, 1970

5. Proceedings of Meeting No. 12 . . . . . AD 721 913
   "Identification and Prevention of Mechanical Failures in Internal Combustion Engines"
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6. Proceedings of Meeting No. 13 . . . . . AD 724 637
"Standards as a Design Tool in Surface Specification for Mechanical Components and Structures"
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T. Robert Shives and William A. Willard, Editors

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WASHINGTON, D.C. 20234

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Center for Materials Science, National Bureau of Standards, Washington, DC 20234; Naval Air Systems Command, U.S. Dept. of the Navy, Washington, DC 20360; Office of Naval Research, U.S. Dept. of the Navy, Arlington, VA 22217; National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD 20771

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

These proceedings consist of a group of 34 submitted entries (32 papers and 2 abstracts) from the 33rd meeting of the Mechanical Failures Prevention Group which was held at the National Bureau of Standards, Gaithersburg, Maryland, April 21-23, 1981. The subject of the symposium was maintenance technology improvement through innovation. Areas of special emphasis included maintenance concepts, maintenance analysis systems, improved maintenance processes, innovative maintenance diagnostics and maintenance indicators, and technology improvements for power plant applications.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

fault detection/location system; lubrication; maintenance; maintenance management; maintenance technology; manpower utilization; reliability assessment.

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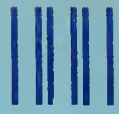

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