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Description of a Discovery Process Modeling System To Forecast Future Oil and Gas Incorporating Field Growth-- ARDS Ver. 5.01

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Table of Contents:

List of Figures:

List of Exhibits:

1. PURPOSE

The purpose of this report is to describe an oil and gas supply forecasting system, called ARDS (Arps-Roberts Discovery System), which incorporates field growth, and is based upon the Arps-Roberts discovery process model (Schuenemeyer and Drew, 1983). The specific version to be discussed in this report is called ARDS 5.01. Discovery process models are statistical models that have a basis in geology. ARDS uses historical drilling and discovery data to forecast the number and size distribution of fields remaining to be found. It is to be applied in partially explored areas that have seen some discoveries. A certain amount of structure or regularity in the historical data is required. This structure includes the fact that, on average, the larger fields are found early in the discovery sequence. ARDS works best when used in geologically homogeneous areas called a play, however, with proper care it can be applied to regions where less stringent requirements exist. For example, in the 1995 national assessment of United States oil and gas resources (U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995), ARDS was used in larger regions.

The forecasting system described in this report allows for growth of individual fields before making a forecast, so that the discovery process model will be operating with more accurate data (see Drew and Schuenemeyer, 1992). Onshore and offshore growth models are available. It also has the ability to forecast the number of small fields remaining to be discovered. Recent changes to the model also permit estimation in certain instances when data sets are small and not well behaved.

The organization of this report is to first describe the model (section 2). Following this, the input data and major results are presented (section 3). The system is described in section 4 and operating procedures are given in section 5. The individual computer programs, which constitute the system, are explained in section 6, and section 7 describes an example, which is given in Appendix A. In section 8 we outline plans for future work. Output data files are presented in exhibits 1 through 10.

The user of this model should be generally familiar with oil and gas exploration data and have a basic understanding of the concepts of statistical variability and modeling. The user will need to install and execute a series of Fortran programs and should have the facility to graph computer output.

2. THE MODEL

2.1 Description

The model used in this system is actually a class of models with various options. The basic model, however, is a modified Arps-Roberts (AR) model which estimates the number of undiscovered fields within size class using historical drilling and discovery data. The size class is typically expressed as a range of values in logarithms of barrels of oil equivalent (BOE). The functional form of this model is:

$$F_i(w) = F_i(\infty)(1 - \exp(-c_i A_i w/B)) + \varepsilon$$

where

i is the i th size class,

$F_i(w)$ are the number of fields found by w cumulative wildcat wells,

$F_i(\infty)$ are the total number of fields in the play,

c_i is the discovery efficiency,

A_i is the mean surface projection area of fields,

B is the play size, and

ε's are identically, independently distributed errors with mean 0 and constant variance.

$F_i(\infty)$ and c_i are model parameters estimated from the discovery data ($F_i(w)$, w). The (assumed) known constants are A_i and B. An example of a reasonable fit to an AR model is shown in figure 1.

Sometimes a change in the historical discovery data results in a significant lack of fit of the AR model. This is often observed near the start of exploration and might be attributable to learning where to site wells or it might be caused by multiple plays. One approach to modeling this type of data is a piecewise linear-Arps Roberts model (called LAR). When this option is chosen, ARDS will attempt to fit the following model:

$$F_{i3}(w) = \begin{cases} F_{i1}(w)k_i w + \varepsilon, & w \leq \alpha \\ F_i(\infty)(1 - \exp(-k_{i_i}(w - \gamma)) + \varepsilon, & w > \alpha, w > \gamma \end{cases}$$

where $k_i = c_i A_i / B$. An example of a data set that is best fit by this model is given in figure 2. The parameters to be estimated in the LAR model are: $F_i(\infty), c_i, F_{i1}, \alpha$ and γ. Those of most interest are $F_i(\infty)$ and c_i. In ARDS, the user is given the choice of running the AR, the LAR, or the best fit between the two.

2.2 Restrictions and Limitations

The model parameters are estimated in program AEST.FOR using a non-linear least square estimation procedure. Occasionally such procedures converge but give unrealistic values for parameter estimates. To mitigate such problems, the ARDS 5.01 **restricts the estimate of discovery efficiency** $\hat{c}_i$ to be less than or equal to 99. Also the **estimate of the ultimate number of fields** in a given size class $\hat{F}_i(\infty)$ is restricted to be less than or equal to four times the number of discoveries in size class i. These restrictions can be changed by simple modifications to program AEST.FOR.

The ARDS 5.01 model provides reasonable estimates of parameters for the data shown in figures 1 and 2 and even functions well when data is moderately ill conditioned. However, it will not provide meaningful estimates when given the data shown in figure 3. The second upturn in the discovery curve shown in figure 3 might be the result of a second play offset in time from the first play, or it may have resulted from the introduction of new technology, access to a previously restricted area or a significant increase in price. When this phenomenon is observed, the investigator should make every effort to determine the cause and disaggregate the data. Even when ARDS converges in this situation, the resultant estimate of c_i will be too low and the resultant estimate of $F_i(\infty)$ too high.

3. DATA REQUIREMENTS, OPTIONS AND PRINCIPAL OUTPUT

3.1 Data Requirements and Conventions

Ideally the input to this system would be discovered fields on a scale of wildcat wells, i.e., each field would be identified by its discovery well, where the discovery wells in an exploration play are ordered by date. Thus a data set consisting of n fields ideally would be of the form $\{(w_j, V_j), j = 1,\ldots,n\}$, where w_j is the cumulative wildcat well (number) that discovered field V_j. The field size V must be a unit of volume of oil or gas. Often these "connected" data sets are not available but the investigator knows the number of wildcat wells drilled by year and the dates of discoveries. The input requirements for ARDS are setup to handle this latter case, namely that there is a field file containing discovery information, and a well file. Note that a "connected" data set should be used when available. How this is accomplished will be addressed later.

The field file must contain the discovery date, estimates of the ultimate oil, natural gas, and natural gas liquid or BOE, and the spatial area of each field. In addition, the field name and its geographic location, if present, are also read from the field file. The field file (figure 4) used in this report was derived from Nehring data (NRG Associates, Inc., 1986). The field file must be sorted in ascending order by discovery year. (It is not necessary for the file to be sorted by month and day.) The well file (figure 5) contains years and wildcat wells per year. The field file and the well file are merged so that sizes of discoveries will be placed on a scale of wildcat wells. A more complete description of the merge is given in section 6.2.

A question that is frequently asked concerns the minimum size of the data set needed to run ARDS. Unfortunately there is no simple answer to this question. We have successfully run ARDS with a data set containing only 30 discoveries and have failed to produce reasonable results with data sets containing several hundred observations. Basically if data is well behaved, i.e., a decline in the number of discoveries with respect to cumulative wildcat wells has been observed, there is consistency among class sizes, namely the degree of decline is proportional to size class and, the variability with size class is small, relatively few observations will be required. Often large data sets can be disaggregated using exogenous information when problems with convergence occur. We have observed, however, that the ARDS model is relatively robust to minor inconsistencies in the data.

The units of oil in the input file, fn.fld can be either millions or billions of barrels of oil and the units of gas can be millions or trillions of cubic feet, however, internally and on ARDS generated reports the units are in millions of barrels of oil equivalent (BOE). For the area of fields the user may select among acres, square kilometers and square miles, however internally and on ARDS generated reports the units are in square kilometers.

The file designator convention used in ARDS is to have the user assign a name to a play, such as p653. This will be referred to generically as fn and must be at most 10 alpha-numeric characters. The field file used by this system must be named "fn.fld" (i.e., the suffix must be fld). The well file used by this system must be named "fn.wel".

3.2 Options

The following options are available in ARDS. Some have been discussed in the previous section; others will be explained later in this report.

1. User specified units of the volume and area of field size.
2. An option to process oil, gas, or oil and gas fields.
3. Pre-specified or user-defined field-size classes.
4. User specified well increments, which are used to summarize historical data.

5. Length of data series (number of wells or dates) used for estimation.
6. Growth or no growth for fields--an onshore and an offshore growth model are available.
7. Negative exponential or piecewise-linear negative exponential models.
8. Estimation of small fields.

3.3 Output

Data files created by ARDS will be labeled fn.suffix, where the suffix is a two or a three-character designator for the type of file created. An example of each file (except for files that only transfer information between ARDS programs) is given in exhibits 1 through 10 at the end of this report. The content of these files will be discussed later. In addition, most programs produce print files designated by the program name followed by the suffix PRN. These are log files that contain intermediate results and information about possible program or data errors. They should be viewed before proceeding to the next program in sequence.

The major output of this system is estimates of the remaining volume and numbers of oil and gas to be discovered by size class. Estimates are also disaggregated into small fields and large sized fields. In addition, when a growth option is chosen, estimates of uncertainty associated with growth are provided. File "fn.dt" (exhibit 2) is a discovery table, which contains cumulative wildcat wells and the corresponding cumulative number of discoveries by field size class. It can be used to analyze ungrown fields. File "fn.dp" (exhibit 3) is the merged field and well file. The basic statistics file "fn.stb" (exhibit 4) contains information on actual discoveries by class and BOE discovered. In file "fn.con" (exhibit 10) are the constants and other input data necessary to recreate a run. These and other files are discussed in detail in section 6.

4. SYSTEM DESCRIPTION

The system consists of a series of Fortran programs, which perform the basic calculations. We illustrate the output at various stages in the modeling process using Systat DOS version 5.02 (SYSTAT, Inc., 1990) macros. The user is also strongly encouraged to do the same. The data is written to files in ASCII format and almost any commercially available plotting program can be used. A brief description of each program shown in figure 6 follows. The input and output files are listed by program in figure 7. A more detailed description of the programs is given in section 6.

Program AFORMAT.FOR

reformats the field file and estimates missing discovery dates.

Program AMERG.FOR

merges the field and well files and estimates missing areas.

Program ADTABLE.FOR

generates summary statistics and prepares a file to be used as input to the growth program AGROW.FOR. Note that if fields are on a scale of wildcat wells, ADTABLE.FOR will be the initial program. The input well-field file is fn.dtw.

Note: At this point the user should plot the cumulative discoveries versus cumulative wildcat well as given in file fn.dt. This can be accomplished by using program APPPLOT.FOR and Systat or with another commercial plotting package figure 8). (See section 6.4 for a description of program APPPLOT.FOR.)

Program ASAREA.FOR

estimates the missing average areas and smooths those present. The resultant smoothed basic statistics file "fn.stb" and the field file "fn.dp" produced by ADTABLE.FOR serve as input to AGROW.FOR.

Systat macro ASAREA.CMD

plots the average surface projection area versus average volume for each size class.

Program AGROW.FOR

grows fields from a given year to a given year. Four growth options are available. One is for no growth. A second, estimates the year of mortality and grows fields according to a model fit to offshore data. The third is an onshore model that consists of two-growth rate tables (figure 9). The fourth (not yet implement) is for a user specified world oil growth model. These models are described in section 6. The output from AGROW.FOR is a set of a 101 discovery tables (file "fn.dtr"). Each table within this set contains a replication number, cumulative wildcat well numbers, and cumulative discoveries by class sizes. (The 101 replication number was chosen to provide reasonably consistent estimates of ultimate resources.) This data together with file "fn.stb" serves as input to program AEST.FOR. When fields are grown, the estimated growth for each replication is produced (file "fn.gro").

Program AEST.FOR

is a nonlinear estimation program. It estimates the parameters of the AR and/or LAR models for each replication generated by AGROW.FOR.

Program ARESULT.FOR

produces estimates (when growth is specified) of the remaining BOE for each replication and then computes quantile estimates (at 10, 50, and 90 percent) of the remaining BOE. Also produced are quantile estimates of growth, and estimates of the mean and trimmed mean. These reflect estimates of uncertainty due to field growth. When the no-growth option is chosen, only a single suite of estimates is generated. The major output information is in files fn.fsd and fn.ult.

Program ACON.FOR

prints information (figure 10) from the fn.con file and the fn.stb file that provides the user with the suite of parameters and constants used to generate the final output. With this information and files fn.fld and fn.wel the user can regenerate all of the output.

5. OPERATING PROCEDURES

5.1 General Information

The total time to run ARDS for p653, a play with 646 fields, is less than one hour on a 90 MHz Pentium personal computer (play p653 has 646 fields). The user can stop the system after completing any Fortran run and resume processing ARDS later.

Two programs (AMERG.FOR and AGROW.FOR) require continuous (0 to 1) uniform random numbers. A random number seed can be entered from the keyboard or the program will choose one by accessing the tenths and hundredths of seconds from the system clock. The random numbers are obtained by calling Microsoft subroutines SEED (once) and RANDOM (as needed). Note that Microsoft uniform random numbers will differ between a 16 and 32-bit machine, even when the same seed is used. Another uniform random generator could be easily substituted.

The Fortran programs have been dimensioned for a maximum of 25 class sizes in all of the programs using a Fortran PARAMETER statement. If there are more than 25 classes, these statements will need to be changed and the programs recompiled. A maximum of 62,999 cumulative wildcat wells is allowed and is represented in the PARAMETER statement of programs ADTABLE.FOR, AGROW.FOR, AEST.FOR, and ARESULT.FOR as 629, for six hundred and twenty-nine, 100 well increments. In addition, a maximum of 101 replications is allowed. The PARAMETER statements in AEST.FOR and ARESULT.FOR would need to be modified to increase the number of replications.

ARDS is interactive and typical information requested by the computer is found in the example presented in Appendix A. We suggest that the user review this example and the remainder of this report before running the system. Only supplemental information needed to run the programs will be presented here.

5.2 Installation, Loading and Compiling Programs for DOS

Store the Fortran programs, the data, and Systat macros (if you choose to use this system for plotting) in the directories as follows:

a. Make a directory called ARDS.

b. Copy the Fortran programs into it. All of the Fortran source programs have the extension FOR.

c. Make a subdirectory called DATA.

d. Copy the Systat macros (having extensions CMD) into it.

e. Copy the data sets "fn.fld" and "fn.wel" into subdirectory DATA. Note that the field file and the well file must have extensions fld and wel respectively. Note also that file "fn.fld" must be sorted by discovery year (columns 186-189).

f. If the U.S. onshore growth model is to be used, file "GRONS.DAT" must be copied into the DATA subdirectory.

g. All programs were compiled by the authors in Fortran 90 (Microsoft Fortran PowerStation, Version 4.0, 1995). Subroutines are compiled in the ARDS5A.LIB, which should be copied into directory ARDS. To compile a program, specify the program name with the FOR suffix and ARDS5A.LIB. For example, to compile AFORMAT.FOR, type:

FL32 AFORMAT.FOR ARDS5A.LIB

Note that this compile is for a 32-bit system (usually a Windows 95 operating system). You may use either upper or lowercase letters when typing Microsoft compile commands. For a 16 bit Microsoft compile you will need to use the command FL AFORMAT.FOR ARDS5.LIB, where ARDS5.LIB is the 16-bit version of the ARDS subroutine library.

5.3 Running the System

5.3.1 General Instructions

A system flow chart is given in figure 6 and an example, which includes the dialogue between terminal and user, is presented in Appendix A. An introduction to the example is found in section 7.

5.3.2 Fortran Programs

All Fortran programs must be run from the ARDS\DATA directory. Entering the name (without extension) of the main program runs them. For example, to execute AFORMAT from subdirectory DATA (ARDS\DATA), enter AFORMAT.

Note: A yes or no ("y" or "n") reply to a question asked by a program must be entered in lowercase. Program and macro names can be entered in upper or lowercase. The user must follow a consistent convention (upper or lowercase) for entering file names. In the instructions that follow, bold letters denote the information to be entered (except for directory names).

5.3.3 Data

All files created by either Fortran programs or Systat macros will be written to the ARDS\DATA directory. A list of input and output files generated by program is given in figure 7. The user will be informed of any file to be overwritten by a program except for the print (PRN) files and can stop and rename that file if desired. The user will be prompted for any information requested from the terminal.

5.3.4 Running ARDS

Make sure that you are in the ARDS\DATA directory. To run ARDS begin by typing the name of the first program, namely AFORMAT. Each program, upon successful completion will identify the subsequent program to be run. A systems flow chart is given in figure 6. All programs operate interactively and will request needed information from the user.

6. PROGRAM DESCRIPTIONS

A description for each of the Fortran programs and plot routines (Systat macros) used in this system follows. It is presented in the order in which they would normally be run. Programs are available from the authors on a 3-½ inch diskette. The user should refer to figure 6 to follow the run sequence. The connecting arrows in figure 6 are for a growth option run. The order of program execution is the same when the no-growth option is chosen (in **AGROW**.FOR) but the file transfer of information is somewhat different. Parameters and constants used by the Fortran programs are written to a file called "fn.con" (see exhibit 10 for an example). For simplicity, file "fn.con" outputs are not shown in figure 6. They are, however, listed in figure 7.

6.1 **AFORMAT**.FOR

Program **AFORMAT**.FOR estimates missing discovery months and days, as necessary, computes BOE, sorts fields by discovery month and day within year, and reformats the data for program **AMERG**.FOR. This output is contained in file "fn.ytw". A missing month is estimated by randomly selecting an integer 1 through 12. Records containing missing discovery years are discarded. Output file "fn.tcw" (exhibit 1) establishes a date-to-cumulative well correspondence, which can be used to help interpret graphs plotted on a scale of cumulative wildcat wells.

6.2 **AMERG**.FOR

Program **AMERG**.FOR merges the Nehring field file output from program **AFORMAT**.FOR (file "fn.ytw") and the well file "fn.wel". The well file (figure 5) contains the year and number of wells by year. Column two contains total exploratory wells per year (Lahee classes 2 through 5). Column four, if present, contains new field wildcats per year (Lahee class 5). Either column can be selected.

A cumulative well number is assigned to each discovery by dividing the Julian day of discovery by 366 and multiplying by the number of wildcat wells in the year of discovery. If the well file contains fewer discovery wells in a given year than there are discoveries, the minimum required number of wells is added. An output of this program (file "fn.dtw") serves as input for **ADTABLE**.FOR. If discoveries are available on a scale of wells, those data should be used. Program **AMERG**.FOR also estimates the area of a field, if missing, from the corresponding volume (in BOE) using the following model specified in function AREST:

$$\text{area}=\exp(b0)*\text{BOE}^{b1}$$

If the volume (BOE) is missing, the record is discarded. Parameters b0 and b1 are estimated using ordinary least squares fit to the log of the above model. A table "fn.tcw" that lists years and cumulative wells is also generated.

6.3 **ADTABLE**.FOR

Program **ADTABLE**.FOR generates a discovery table ("fn.dt"; see exhibit 2, a discovery file ("fn.dp"; see exhibit 3) and a table of basic statistics using the merged well-field file "fn.dtw" as input. The user is asked to supply the play size and choose a log-based class size that is needed by the Arps-Roberts discovery process model. In class sizes where no discoveries are present, the expected volume of oil is computed as geometric mean of the class size (in BOE) boundaries. Volumes and areas in other size classes are the arithmetic average of the observations. Output of

ADTABLE.FOR (written to print file ADTABLE.PRN) links cumulative wildcat wells with calendar dates and provides running sums of BOE. Also, the user can hide a portion of the field/well data and use it to evaluate the model. When this option is chosen additional files ("fn.dpf", "fn.dtf" and "fn.stf") are created to store the forecasted interval data.

6.4 **APPPLOT**.FOR

APPPLOT.FOR is a pre-processor for plotting cumulative discoveries versus cumulative wells using Systat. (It should be omitted if another graphic package is used.) We strongly encourage users to make this plot because it can reveal possible shifts in the data or other factors that would bear further investigation. Program APPPLOT requires a data file, APPPLOT.DAT to be loaded in the DATA subdirectory. The data that can be plotted are in files fn.dt and fn.dtr. Program APPPLOT.FOR generates a Systat macro plt.cmd. To run this macro, type macro and then submit plt.cmd.

6.5 **ASAREA**.FOR

ASAREA estimates surface projection areas for classes that do not contain data. It also smoothes the areas across size classes. The model used is:

$$\log(\text{ave area}) = \text{const}+b_1*\log(\text{ave BOE})+b_2*\log(\text{ave BOE})**2$$

It is fit by a Tukey bi-weight robust regression procedure because this fitting procedure is less sensitive to outliers (points far from the regression line) than is ordinary least squares. The user should view the residuals and change the model as needed, since this equation may not be the best model for all situations. In addition, it may be necessary to down-weight or delete areas associated with small class sizes that contain few fields. This program creates a file called fn.stb reproduces the information in fn.sta and adds smoothed areas (see exhibit 4).

6.5.1 Systat Macro **ASAREA**.CMD

ASAREA.CMD plots the smoothed and raw average BOE versus average surface projection area (using file "fn.stb" as input) and the log(ave BOE) versus log(ave area).

6.6 **AGROW**.FOR

Program **AGROW**.FOR grows the original fields (in BOE), as given in file "fn.dp" (exhibit 3), and produces cumulative discovery tables. The process of growing fields is repeated 101 times. A representative sample of the output file "fn.dtr" is given in exhibit 5. The default number of replications (101) gives reasonably stable estimates of remaining BOE (which will be estimated by program **AEST**.FOR). Two growth models, an onshore and an offshore, are available. Fields can be grown from a base year, usually the year the field file was last updated, to a specified year in the future. For the onshore model, the user can choose either field or reservoir growth. When the offshore model is chosen, an estimate of the year when production will cease is made for each field. Fields are then grown to the minimum of the year of mortality or the year specified to end growth. A brief description of the mortality and growth modules follows. Additional details are given in Schuenemeyer and Drew (1996).

The mortality model is implemented as subroutine EXPPF. The probability of a field of size S surviving to age A is estimated using loglinear regression and the Western Gulf of Mexico data to be:

$$p_s(A,S) = b/(1 + b),$$

where $b = \exp(-4.491 - 0.213*A + 0.813*S)$ and $S = \log_2(X/0.00593) + 2.5$. X is the field size at expiration in millions of BOE. The following algorithm is used to estimate the year of expiration of a field:

a: Let nc $\Leftarrow$ nfb - ny + 1, where nfb is the year the forecast is to begin and ny is the year of discovery,

b: d $\Leftarrow$ p_s(nc-1,x), the probability of a field of size x surviving at least nc-1 years,

c: u $\Leftarrow$ u(0,1), a uniform random number,

d: my $\Leftarrow$ nfe - ny, where nfe is the year the forecast is to end,

e: if (u < p_s(my,x)/d) then the field will <u>not</u> expire in the forecast period, else

f: for i = nc to my: if (u $\geq$ p_s(i,x)/d) then go to step h; note that p_s(i,x)/d is the conditional probability of survival of a field of size x.

g: field does not expire in the specified time.

h: field will expire in year nye $\Leftarrow$ ny + i.

The onshore growth model is given in subroutine GRONSH. It computes yearly growth for either fields or reservoirs based upon a table (in data set "GRONS.DAT") supplied by Emil Attanasi of the U.S. Geological Survey and included in the ARDS 5.01 packet of programs. See Attanasi and Root, 1994 for a discussion of the U.S. domestic oil and gas growth models. For growth purposes, a field is classified as an oil field if the fraction of oil is greater than 0.23 on a BOE basis (ignoring liquid natural gas) and is classified as a gas field otherwise. This is equivalent to a classification of a field as gas if the gas to oil ratio is greater than 20,000 cu. ft to 1 bbl oil, assuming 6,000 cu. ft. of gas to one barrel of oil. We assume that the growth error is normally distributed with mean 0 and standard deviation 0.045781 (the standard deviation estimated for the offshore model).

The offshore growth model is given in subroutine GRMODR. The incremental average field growth data for the Miocene-Pliocene trend in the western Gulf of Mexico (Drew and Lore, 1992 and Drew and Schuenemeyer, 1992) was fit to the following model:

$$\log[G(A,S;n_{a,i[S]})] = \beta_0 + \beta_1 A + \beta_2 S + \varepsilon$$

where G is the ratio (averaged over $n_{a,i[S]}$ observations) of fields of age A to fields of age A-1 of size S (in BOE). In the Miocene-Pliocene data used to fit this model, S={9,10,...,17}, A={1,2,3,...,41} and $n_{A,i[S]}$ is the number of fields (observations) of size S (size class i[S]) at age A. The n's vary between 1 and 66. Weighted (by the n's) least squares and robust procedures were used to fit the model. Since the results were similar, the weighted least squares estimates are reported. The estimates for the model parameters are:

$$\hat{\beta}_0 = 0.177980 \; (0.005305)$$
$$\hat{\beta}_1 = -.007165 \; (0.000425)$$
$$\hat{\beta}_2 = -.002063 \; (0.000098)$$

The standard errors are given in parenthesis. The F ratio at 2 and 4273 degrees of freedom was 699. The estimated standard deviation (the square root of the mean square error) of the yearly growth for a field of size S is $\hat{\sigma} = 0.04578$. The error for the growth model was assumed to be normally distributed. An analysis of residuals and other diagnostics indicates that model assumptions have been met. Thus, $\hat{G} = \exp(0.177980 - 0.007165\,S - 0.002063\,A)$, $\hat{G} \geq 1$ and $G_r = \hat{G} + r$, $where\ r \sim N(0,\hat{\sigma}^2)$.

In both the onshore and the offshore growth models, the growth multiplying factor G_r is restricted to be greater than 0.001. Note, that because of the presence of a random deviate r, shrinkage (G_r<1) can occur. The growth multiplying factor G_r is bounded away from zero because this would indicate that a field disappeared through a merger. While possible, this feature has not been incorporated into the model. The estimated field size at age A+1 is the size at age A, times the growth-multiplying factor G_r.

Note that the user has the option of choosing no growth. In this case the fields are essentially passed through **AGROW**.FOR and the model only runs for replication.

6.7 **AEST**.FOR.

This program estimates parameters for either the modified Arps-Roberts (AR) model or the piecewise linear Arps-Roberts (LAR) model using cumulative discoveries versus cumulative wildcat wells in a specified range of size classes. When the field growth option is specified, estimation is attempted for each replication. The models are described in detail in section 2 of this report. The fitting procedure is nonlinear least squares using the Gauss-Newton method. The key input data to this program are the discovery tables generated by **AGROW**.FOR (see exhibit 5). Prior to fitting the cumulative wells versus cumulative discovery data, the data will be shifted (if necessary) so that there is no more than one zero cumulative discovery at the beginning of the series. For example, if (for a given class) the cumulative discoveries for the first three, hundred well increments were 0, 0, and 3, the AR or LAR fit would begin at 200 wells. In **AEST**.FOR the user can select an AR fit (option 1), a LAR fit (option 2), or allow the model to choosing the best fit (according to a regression significance test) between the two (option 3).

AEST.FOR requires three major subroutines. They are NLLSLM1.FOR, which is the Gauss-Newton algorithm, and Linpack routines DQRDC.FOR and DQRSL.FOR. These latter routines are called by NLLSLM1.FOR to solve the Gauss-Newton algorithm via a Householder transformation. In NLLSLM1, subroutines FCODE1 and PCODE1 contain the AR model and first derivatives with respect to the parameters, respectively. The model for LAR is given in FCODE2. LAR estimation uses numerical derivatives. The output (file "fn.pem") contains estimates of the ultimate number of fields, discovery efficiencies, the number of discoveries (as determined by growth model), and the sum of squares error of the fits (see exhibit 6).

We suggest using the class size of the average modal class (supplied by the program) as the minimum size class for estimation in **AEST**.FOR. Smaller class sizes are subject to economic truncation and, in addition, it may not be possible to obtain convergence. An error message will be printed should this occur and the user should examine graphs of the data. ***Convergence of model***

will be difficult to obtain when the relationship between cumulative discoveries (on the vertical axis) versus cumulative wildcat wells (on the horizontal axis) is straight or concave up (each successive well finds more discoveries). The relationship between discoveries and wells may be concave up for a short period due to random chance. The cause of a concave up trend that exists over a long time period may be due to structural changes such as an advance in technology or access to a new area. When this occurs, the user should try to pinpoint the source of the problem and, where possible, disaggregate the data. If the discovery efficiency in a given class is less than one and the discoveries appear to be found at approximately equal increments of exploration (i.e., a plot of cumulative discoveries versus cumulative wildcats is linear), the play (basin) size may be too small. The user should try increasing the play size. Finally, the largest size class used for estimation should contain at least three discovered fields.

For the no-growth option (specified in AGROW) only one replication will have been generated. When growth is specified, 101 data sets containing grown fields will have been generated. An estimate of the remaining BOE for each replication is computed. Note that for very small or extremely ill-behaved data sets, some replications may not contain enough classes for the model to produce a reliable estimate of the remaining BOE. At least four classes in a given replication must converge. When this does not happen, the replication is omitted.

6.8 **ARESULT**.FOR

Program **ARESULT**.FOR computes estimates of the volume of BOE remaining to be discovered. If requested by the user during input, this program also estimates the number of small fields remaining to be discovered using a geometric ratio procedure (see Schuenemeyer and Drew, 1983). Estimation of the geometric ratio begins in one class size larger than that used as the beginning class size in **AEST**.FOR. The right-hand end of the class size distribution is truncated when four or fewer fields have been discovered in a given class since size classes containing fewer fields are judged to be too erratic to be used in the estimation of the geometric ratio. Alternatively, the user can supply a geometric ratio.

The estimate of the remaining BOE is divided between small and large field sized class estimates. (Large field size classes are defined to be those that can be estimated directly from the model as opposed to being estimated from the geometric ratio.) From the distributions of the volume of BOE remaining to be found in the large field size classes (growth option only), the 10, 50 and 90 percent quantile estimates are obtained. The mean and 80 percent-trimmed mean are also computed. Quantiles for growth are estimated independently of remaining BOE using growth data transferred from **AGROW**.FOR. The remaining BOE, growth and geometric ratio for each replication are given in file "fn.rem" (see exhibit 7). The mean and trimmed mean are also computed for growth. The summary output is in file "fn.fsd" (see exhibit 8). The ultimate number of fields and volume of BOE remaining to be discovered is given in file fn.ult (see exhibit 9). The small field size class estimates are indicated with an asterisk in exhibit 9. Efficiency estimates are not used when making small field size class estimates, only the geometric ratio. When growth is specified, these results are given for the 10, 50 and 90 quantiles based on the volume of BOE remaining to be discovered in the large field size classes. Finally, all of the parameters and constants used in a run of ARDS are given in file p653.con (exhibit 10). These can be printed out (written to file ACON.PRN) using program ACON.FOR.

7. DESCRIPTION OF EXAMPLE

An example from an onshore play denoted as p653 in East Texas is given in Appendix A. It consists of the screen dialogue (input and output) for each of the Fortran programs. Section 5 discuss the procedures to use to run ARDS.

8. FUTURE WORK

The following product improvements are planned for future versions of ARDS:

- Implementation of a sequential procedure to detect when an upward shift begins to occur in the discovery profile (cumulative discoveries versus cumulative wildcat wells).
- Estimate the uncertainty associated with model lack of fit and forecasting error for large field size class forecasts.
- Estimate the uncertainty associated with projections of the estimated remaining number of fields and BOE in small fields.

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Figure 1. Example of Arps-Roberts Model Fit

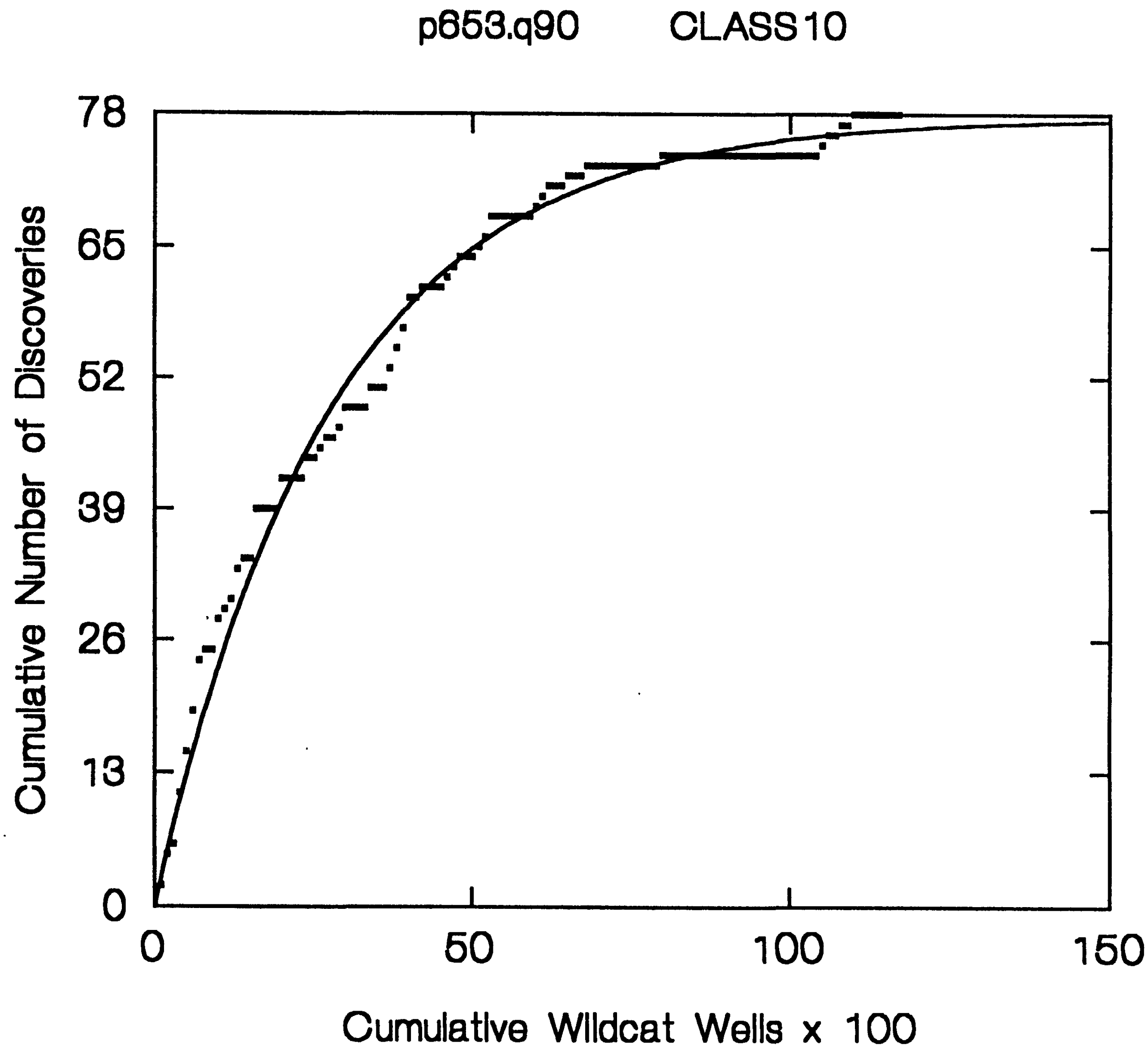

Figure 2. Example of Piecewise Linear-Arps-Roberts Model Fit

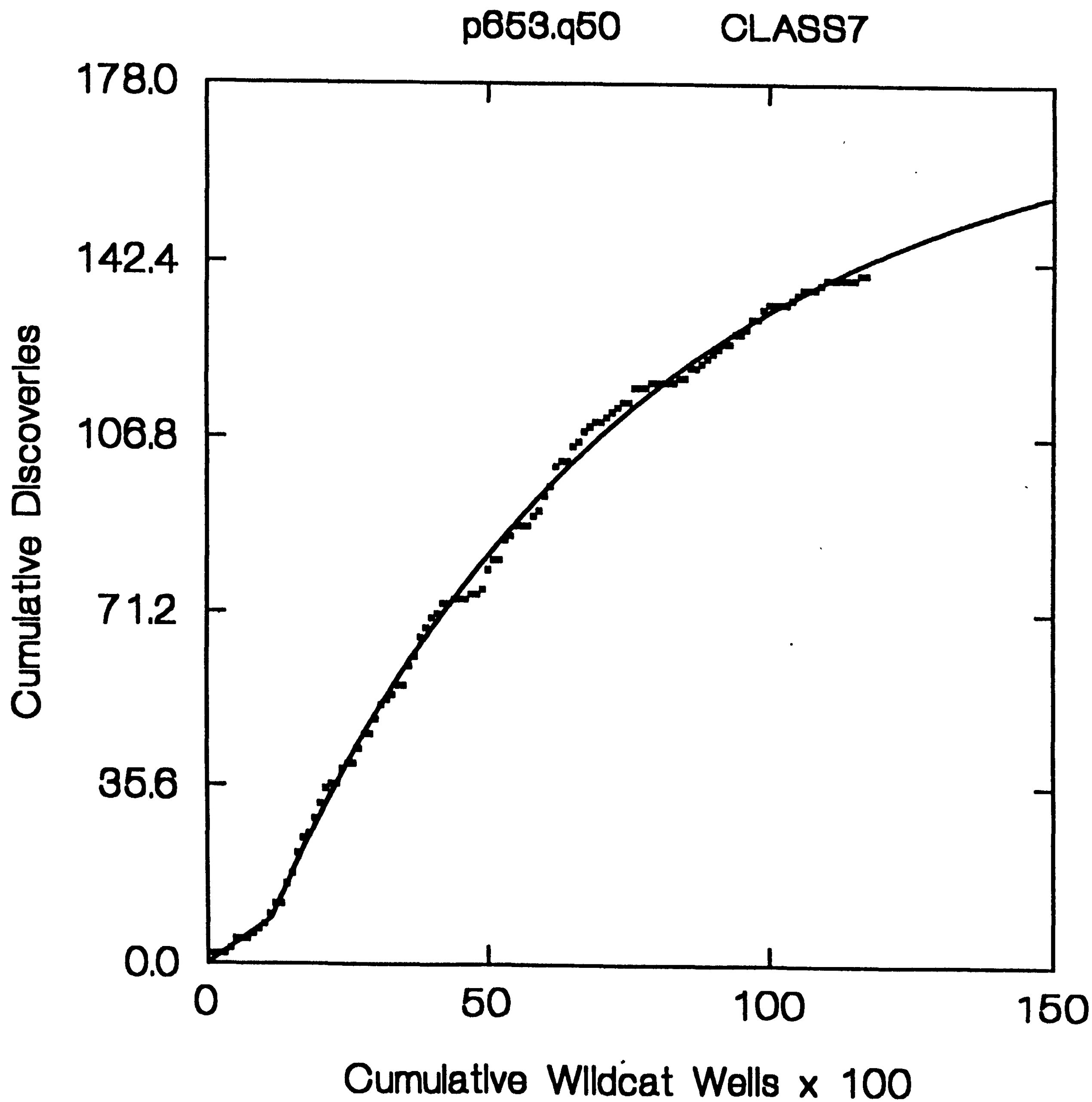

Figure 3. Example of Ill-Fitting Data

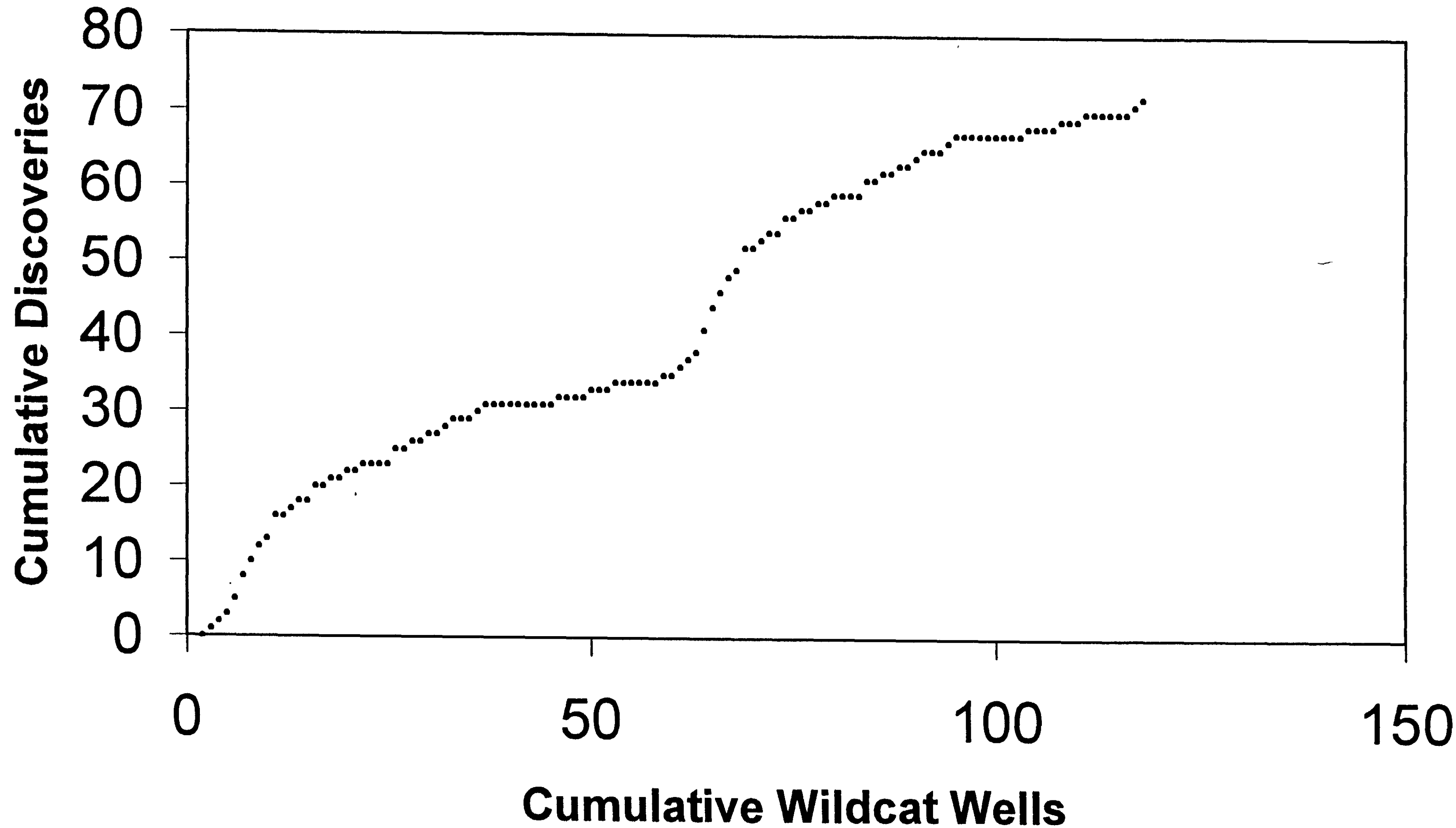

Figure 4. Input (Nehring) Field File Format

POSITION	DESCRIPTION
1-10	NEHRING ID CODE
12-36	FIELD NAME -- 25 CHARACTERS
38-45	LATITUDE F8.5
47-55	LONGITUDE F9.5
57-59	UGSG PROVINCE CODE I3
61-62	YEAR $\quad$ I2
64-73	GAS ANNUAL (MILLIONS CF)
75-84	GAS CUMULATIVE PROD. (MILLIONS CF)
86-95	GAS KNOWN REC. (MILLIONS CF)
97-106	GAS LIQU. ANNUAL (THOUSAND BBL)
108-117	GAS LIQU. CUM. PROD. (THOUSAND BBL)
119-128	GAS LIQU. KNOWN REC (THOUSAND BBL)
130-139	OIL ANN. PROD (THOUSAND BBL)
141-150	OIL CUM. PROD (THOUSAND BBL)
152-161	OIL KNOWN REC (THOUSAND BBL)
163-166	STATE CODE (2 DIGS ST CD, NEXT 2 SUB AREA, MOSTLY 00
168-171	STATE CODE (2 DIGS ST CD, NEXT 2 SUB AREA, MOSTLY 00)
173-176	STATE CODE (2 DIGS ST CD,NEXT 2 SUB AREA, MOSTLY 00)
177-182	MAXACRE I6
186-195	COMPLETION DATE OF DISCOVERY WELL YYYY/MM/DD
198-202	TOTAL DEPTH $=$ TOTAL DEPTH
204-208	TOPINT1 $=$ DEPTH TO PRODUCING INTERVAL 1
210-214	TOPINT2 $=$ DEPTH TO PRODUCING INTERVAL 2

Figure 5. Wildcat Wells by Year, File p653.wel

Year	Wildcat wells
1902	0
1903	0
1904	0
1905	0
1906	0
1907	0
1908	0
1909	1
1910	0
1911	0
1912	0
1913	0
1914	0
1915	1
1916	1
1917	1
1918	1
1919	1
1920	3
1921	7
1922	4
1923	4
1924	5
1925	8
...	...
1971	189
1972	188
1973	167
1974	212
1975	240
1976	218
1977	232
1978	289
1979	268
1980	281
1981	318
1982	270
1983	245
1984	302
1985	232
1986	103
1987	60
1988	56
1989	40
1990	6

ARDS 5.01 Flow Chart

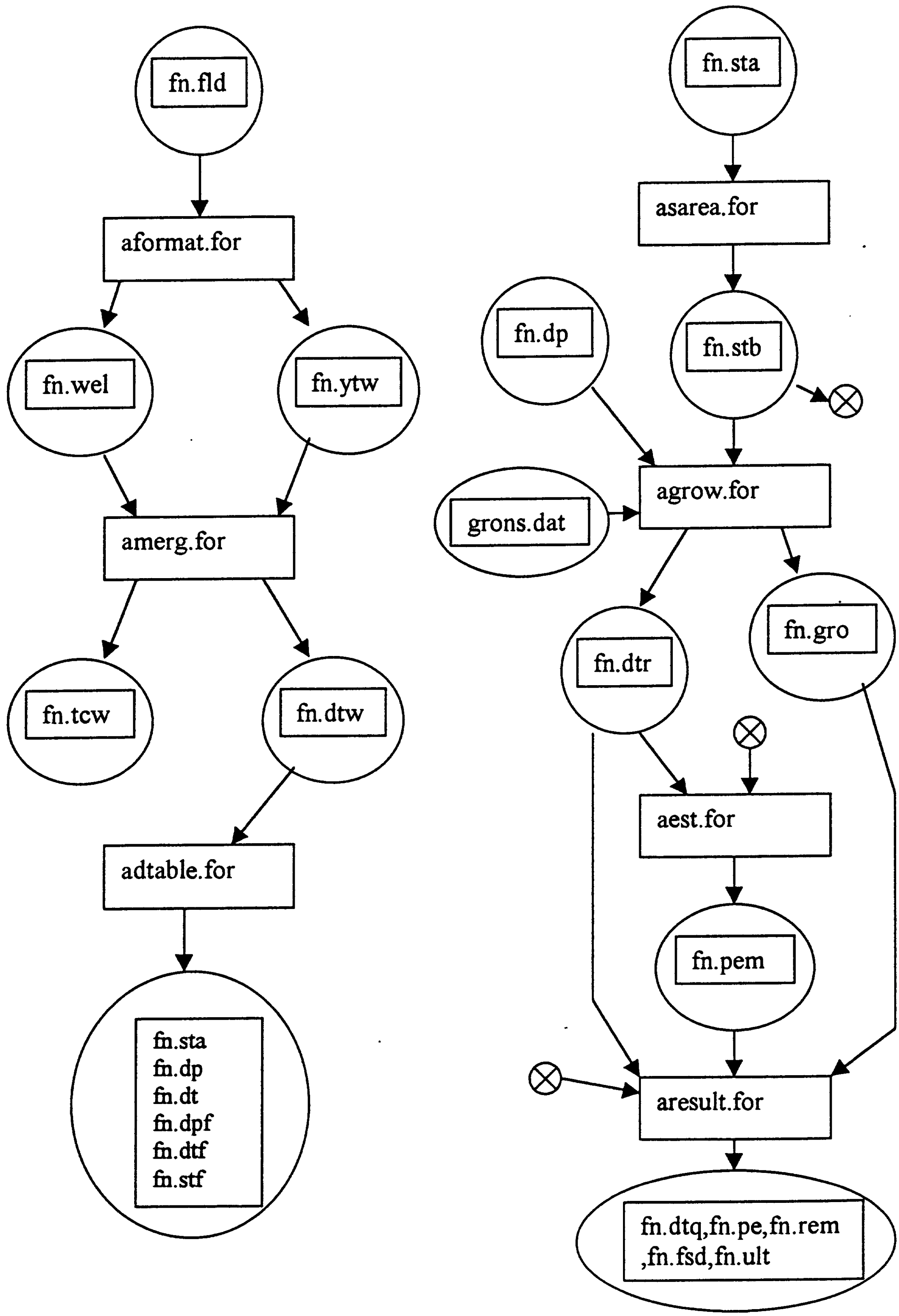

Figure 6

Figure 7. Input and Output Files by Program

Program	Input Files	Output Files
AFORMAT.FOR	fn.fld	fn.con fn.ytw
AMERG.FOR	fn.wel fn.con fn.ytw	fn.dtw fn.tcw fn.con
ADTABLE.FOR	fn.dtw fn.con	fn.dp fn.dt fn.sta fn.con fn.dpf[1] fn.dtf[1] fn.stf[1]
ASAREA.FOR	fn.sta	fn.stb
AGROW.FOR	fn.stb fn.dp grons.dat fn.con	fn.dtr fn.gro fn.con fn.dpr[2]
AEST.FOR	fn.stb fn.dtr fn.con	fn.pem fn.con
ARESULT.FOR	fn.gro fn.stb fn.pem fn.dtr fn.con	fn.rem fn.dtq[3] fn.pe fn.con fn.ult fn.fsd

[1]If forecast option interval chosen.

[2]One replication only.

[3]Not generated for no growth model.

Figure 8

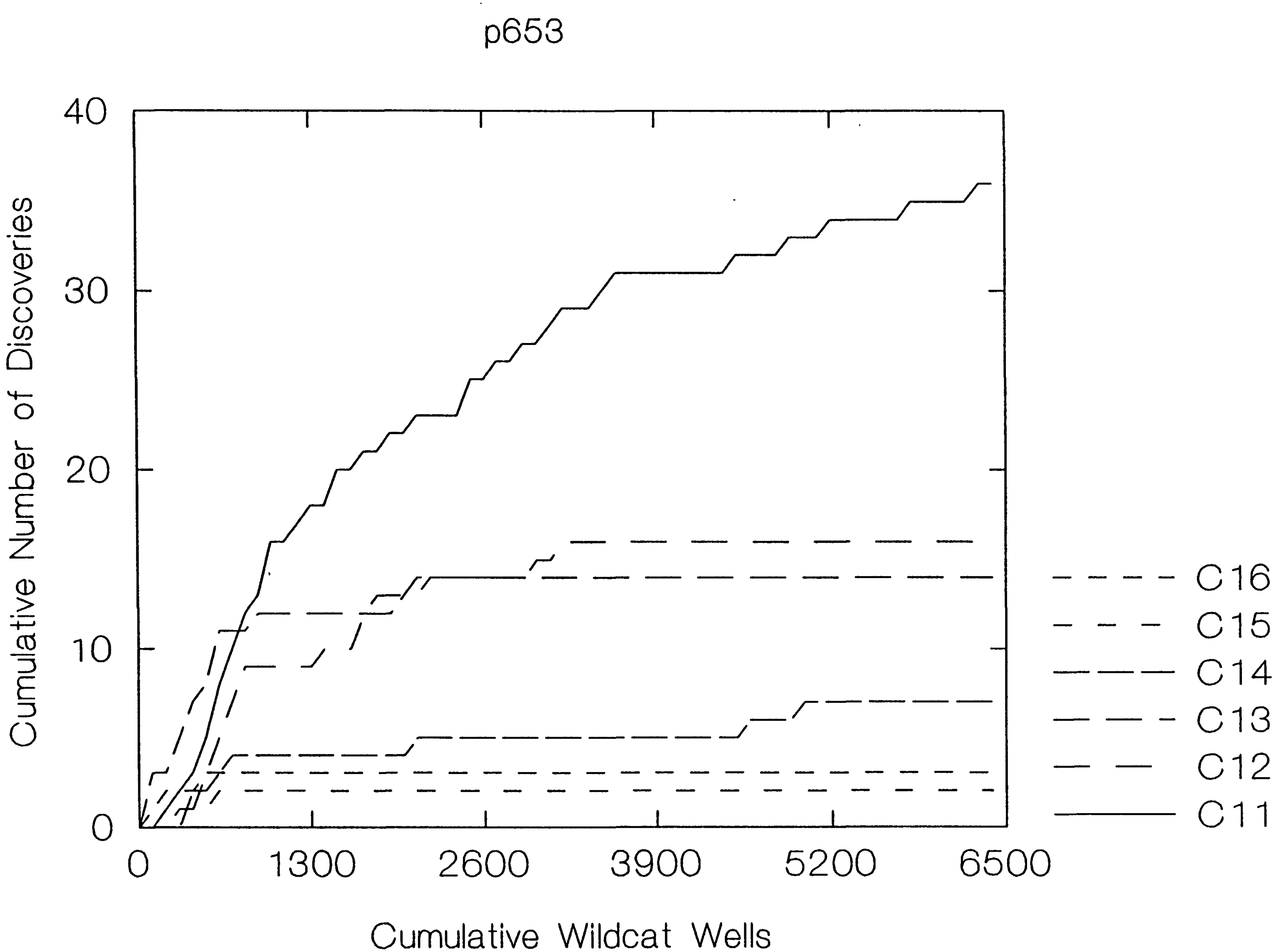
p653
Cumulative Number of Discoveries
0
10
20
30
40
0
1300
2600
3900
5200
6500
Cumulative Wildcat Wells
C16
C15
C14
C13
C12
C11

Figure 9. Onshore Growth Tables

Cumulative Growth (in percent)

Year	-----Field------ Oil	Gas	----Reservoir--- Oil	Gas
0	1.000	1.000	1.000	1.000
1	3.075	2.854	2.788	2.790
2	4.339	4.522	3.786	4.163
3	5.204	5.175	4.554	4.944
4	5.893	5.921	5.062	5.677
5	6.285	6.553	5.335	6.103
6	6.703	7.252	5.622	6.561
7	6.929	7.719	5.781	6.749
8	7.162	8.090	5.944	6.942
9	7.403	8.478	6.111	7.141
10	7.653	8.740	6.284	7.346
11	7.910	8.932	6.461	7.557
12	8.127	9.126	6.643	7.774
13	8.313	9.314	6.814	7.902
14	8.503	9.507	6.989	7.989
15	8.592	9.704	7.057	8.076
16	8.683	9.904	7.125	8.165
17	8.774	10.109	7.194	8.254
18	8.866	10.318	7.264	8.345
19	8.960	10.531	7.334	8.436
20	9.054	10.646	7.406	8.508
...		...		...
70	13.402	16.342	11.107	10.285
71	13.474	16.372	11.165	10.286
72	13.547	16.401	11.223	10.287
73	13.620	16.401	11.282	10.288
74	13.694	16.401	11.341	10.289
75	13.768	16.401	11.400	10.289
76	13.842	16.401	11.460	10.290
77	13.917	16.401	11.520	10.291
78	13.992	16.401	11.580	10.292
79	14.068	16.401	11.641	10.293
80	14.144	16.401	11.701	10.293
81	14.220	16.401	11.763	10.294
82	14.297	16.401	11.824	10.294
83	14.374	16.401	11.886	10.294
84	14.452	16.401	11.948	10.294
85	14.530	16.401	12.011	10.294
86	14.609	16.401	12.073	10.294
87	14.688	16.401	12.136	10.294
88	14.767	16.401	12.200	10.294
89	14.847	16.401	12.264	10.294

Figure 10. Report of Parameters and Constants

```
ARDS v5.01   Date: 11/10/1997  Time: 11:45

File: ACON.PRN, report of parameters and constants

PLAY 653
 Model option: Best AR or LAR
 BOE Scale: log 2 (6=1 mmBOE)
 Well increment for model:   100

 Growth from year 1990 to 2010
 Growth model:Onshore  - Field
  Largest size class-data present in all reps  16

 Random num seed in aformat   4627
 Random num seed in agrow   9034

 Wells - total exploratory
 Cumulative well num of last discovery  11665

 Number of fields used   646
 Type of fields: Oil & Gas
  Unit of input data:
   Oil thousand bbl Gas millions cu ft
   Area acres
  NOTE-in the ARDS files the unit of oil and gas is mm BOE
   Unit of area is sq. km.

 Play/basin size (sq. km.) -     42362.
 Ave modal class size   7
 Beg class size-non linear est.   7
 End class size-non linear est.  16

 Beginning size class for small field estimation   5
 Replication numbers in p653.dtr        for:
    q10  14
    q50  42
    q90  61
   Mean  65

 Size class   Right hand end (Millions BOE)

     1              .063
     2              .125
     3              .250
    ...             ...
    14           512.000
    15          1024.000
    16          2048.000
    17          4096.000
    18          8192.000
```

LIST OF EXHIBITS (SAMPLE OUTPUT FILES)

Exh.	File Name	Generating Program
1	p653.tcw	amerg.for
2	p653.dt	adtable.for
3	p653.dp	adtable.for
4	p653.stb	asarea.for
5	p653.dtr	agrow.for
6	p653.pem	aest.for
7	p653.rem	aresult.for
8	p653.fsd	aresult.for
9	p653.ult	aresult.for
10	p653.con	all previous Fortran programs

Exhibit 1. Year End vs. Cumulative Wildcat Number, File p653.tcw

Year	Cumulative Wildcat
1902	0
1903	0
1904	0
1905	0
1906	0
1907	1
1908	2
1909	3
1910	3
1911	3
1912	3
1913	3
1914	3
1915	4
...	...
1969	7568
1970	7762
1971	7951
1972	8139
1973	8306
1974	8518
1975	8758
1976	8976
1977	9208
1978	9497
1979	9765
1980	10046
1981	10364
1982	10634
1983	10879
1984	11181
1985	11413
1986	11516
1987	11576
1988	11632
1989	11672
1990	11678

Exhibit 2. Discovery Table, File p653.dt

Cum. wildcat well	Cumulative number of discoveries Size class 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
100	0	0	0	0	0	0	2	1	0	2	0	0	3	0	0	1
200	0	0	0	0	0	2	2	1	2	4	1	1	3	0	0	2
300	0	0	0	0	0	2	2	1	3	7	2	1	5	0	1	2
400	0	0	0	0	0	2	4	2	4	13	3	1	7	2	1	2
500	0	0	0	0	0	6	6	2	7	16	5	3	8	2	1	3
600	0	0	0	0	0	6	6	4	12	20	8	5	11	3	2	3
700	0	0	0	0	0	7	6	7	14	27	10	7	11	4	2	3
800	0	0	0	0	0	8	8	10	15	28	12	9	11	4	2	3
900	0	0	0	0	0	8	9	10	18	28	13	9	12	4	2	3
1000	0	0	0	0	0	9	9	13	19	31	16	9	12	4	2	3
1100	0	0	0	0	0	10	11	13	22	31	16	9	12	4	2	3
1200	0	0	0	0	0	11	13	14	26	32	17	9	12	4	2	3
1300	0	0	0	0	0	12	14	15	27	35	18	9	12	4	2	3
1400	0	0	0	0	0	15	17	18	29	37	18	10	12	4	2	3
1500	0	0	0	0	0	17	18	21	31	40	20	10	12	4	2	3
1600	0	0	0	0	0	21	21	25	33	45	20	10	12	4	2	3
1700	0	0	0	0	0	23	24	25	37	45	21	12	12	4	2	3
1800	0	0	0	0	0	25	24	28	38	45	21	13	12	4	2	3
1900	0	0	0	0	0	27	27	29	39	45	22	13	12	4	2	3
2000	0	0	0	0	0	28	31	36	41	46	22	13	13	4	2	3
...								...							...	
9900	0	0	0	0	0	138	121	117	78	73	36	16	14	7	2	3
10000	0	0	0	0	0	140	121	117	78	73	36	16	14	7	2	3
10100	0	0	0	0	0	140	121	117	78	73	36	16	14	7	2	3
10200	0	0	0	0	0	141	121	117	79	73	36	16	14	7	2	3
10300	0	0	0	0	0	142	122	117	79	73	36	16	14	7	2	3
10400	0	0	0	0	0	143	122	118	79	73	36	16	14	7	2	3
10500	0	0	0	0	0	144	122	119	79	73	36	16	14	7	2	3
10600	0	0	0	0	0	147	122	119	81	73	36	16	14	7	2	3
10700	0	0	0	0	0	147	123	119	81	73	36	16	14	7	2	3
10800	0	0	0	0	0	149	126	119	81	73	36	16	14	7	2	3
10900	0	0	0	0	0	151	127	120	81	73	36	16	14	7	2	3
11000	0	0	0	0	0	153	127	121	82	74	36	16	14	7	2	3
11100	0	0	0	0	0	153	127	122	82	74	36	16	14	7	2	3
11200	0	0	0	0	0	153	127	122	82	74	36	16	14	7	2	3
11300	0	0	0	0	0	153	127	122	82	74	36	16	14	7	2	3
11400	0	0	0	0	0	153	128	123	82	74	36	16	14	7	2	3
11500	0	0	0	0	0	153	129	123	82	74	36	16	14	7	2	3
11600	0	0	0	0	0	156	129	123	82	74	36	16	14	7	2	3
11700	0	0	0	0	0	158	130	124	82	74	36	16	14	7	2	3

Exhibit 3. Field File, File p653.dp (headings added)

Discovery number (wildcat well)	Volume MBOE	Size class	Area km sq.	Discovery date YYYYMMDD	-----Percents------ Gas	NGL	Oil
1	220.710	13	24.80	19070128	47.12	5.03	47.85
2	18.910	10	9.10	19080606	4.79	.02	95.19
8	205.080	13	61.00	19190918	47.18	4.84	47.98
9	3.347	7	4.20	19200216	16.43	1.40	82.16
18	5.448	8	9.40	19211218	99.58	.42	.00
23	235.210	13	45.50	19230118	55.69	7.89	36.41
44	23.295	10	17.50	19260602	50.01	2.51	47.48
68	1332.100	16	217.40	19280815	68.88	19.88	11.25
97	2.011	7	7.00	19291120	97.27	1.59	1.14
108	15.895	9	5.90	19300621	37.43	1.98	60.59
121	126.440	12	15.43	19310215	70.78	.27	28.95
140	1.260	6	5.00	19311201	33.73	.00	66.27
145	19.835	10	6.53	19320130	48.65	.93	50.42
153	43.200	11	17.80	19320506	42.13	5.90	51.97
163	1.848	6	.60	19320831	47.08	6.49	46.43
181	12.564	9	3.00	19330402	53.72	.03	46.24
184	1494.460	16	84.50	19330505	34.53	3.24	62.23
186	22.900	10	7.00	19330523	32.31	.00	67.69
203	18.965	10	8.30	19331214	40.86	4.82	54.31
225	564.690	15	31.70	19340508	30.11	2.16	67.74
252	8.979	9	8.40	19341028	11.36	.00	88.64
281	139.140	13	16.13	19350413	52.82	4.84	42.33
282	53.985	11	17.50	19350419	82.43	4.56	13.01
...	...	..	...	....	....	....	....
11577	1.060	6	1.68	19880101	24.53	.00	75.47
11582	1.360	6	1.88	19880202	62.50	8.09	29.41
11620	1.570	6	2.01	19881013	89.17	10.83	.00
11634	2.005	7	2.26	19890112	87.28	12.72	.00
11651	1.680	6	2.08	19890615	65.48	1.79	32.74
11665	4.020	8	3.12	19891024	93.28	6.72	.00

Exhibit 4. Basic Statistics (Area Smoothed), File p653.stb

Size class	Average volume mm BOE	Number of flds found	Total volume mm BOE	Smoothed areas (km.sq.)	Right end size class mm BOE	Unsmoothed areas (km.sq.)
1	.3125000E-01	0	.0000000	1.761554	.6250000E-01	.0000000
2	.8838835E-01	0	.0000000	1.931527	.1250000	.0000000
3	.1767767	0	.0000000	2.130603	.2500000	.0000000
4	.3535534	0	.0000000	2.420192	.5000000	.0000000
5	.7071068	0	.0000000	2.831019	1.000000	.0000000
6	1.427490	158	225.5433	3.419463	2.000000	3.398725
7	2.859417	130	371.7242	4.245590	4.000000	3.979058
8	5.602127	124	694.6638	5.384124	8.000000	5.552815
9	11.49754	82	942.7979	7.156324	16.00000	6.959765
10	22.67801	74	1678.173	9.639074	32.00000	10.65404
11	46.72191	36	1681.989	13.64950	64.00000	13.07518
12	94.17100	16	1506.736	19.71755	128.0000	22.15187
13	178.1572	14	2494.200	28.27948	256.0000	34.89410
14	300.1193	7	2100.835	38.69027	512.0000	39.96001
15	578.0200	2	1156.040	58.73806	1024.000	28.73280
16	1559.720	3	4679.160	116.2056	2048.000	165.3822
17	2896.309	0	.0000000	183.3194	4096.000	.0000000
18	5792.619	0	.0000000	314.0461	8192.000	.0000000

Exhibit 5. Grown Discovery Table Replications, File p653.dtr

Cumulative number of discoveries

Rep	CWW	Size class																
num	100	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1	0	0	0	0	0	0	2	1	0	2	0	0	2	1	0	1	0
1	2	0	0	0	0	0	1	3	1	0	5	2	0	3	1	0	2	0
1	3	0	0	0	0	0	1	3	1	1	8	3	0	5	1	1	2	0
1	4	0	0	0	0	0	1	5	2	3	12	4	2	6	3	1	2	0
1	5	0	0	0	0	0	4	8	2	5	16	6	3	8	3	1	2	1
1	6	0	0	0	0	0	4	8	5	8	18	11	5	11	6	1	2	1
1	7	0	0	0	0	0	5	8	6	12	25	13	7	11	7	1	2	1
1	8	0	0	0	0	0	7	10	8	13	26	15	8	12	7	1	2	1
1	9	0	0	0	0	0	7	10	9	14	28	16	8	13	7	1	2	1
1	10	0	0	0	0	0	8	10	12	15	30	18	10	13	7	1	2	1
1	11	0	0	0	0	0	9	11	13	17	31	18	10	13	7	1	2	1
1	12	0	0	0	0	0	10	12	14	21	33	18	11	13	7	1	2	1
1	13	0	0	0	0	0	10	13	15	23	36	18	12	13	7	1	2	1
1	14	0	0	0	0	1	11	17	16	26	37	20	13	13	7	1	2	1
1	15	0	0	0	0	1	12	19	18	29	40	20	15	13	7	1	2	1
1	16	0	0	0	0	2	14	23	20	31	45	22	15	13	7	1	2	1
1	17	0	0	0	0	2	15	26	21	34	46	23	17	13	7	1	2	1
1	18	0	0	0	0	2	17	26	24	35	46	23	17	14	7	1	2	1
1	19	0	0	0	0	2	17	31	25	36	46	24	17	14	7	1	2	1
1	20	0	0	0	0	2	18	34	29	41	47	25	17	14	8	1	2	1
1	21	0	0	0	0	2	19	35	34	41	48	25	18	15	9	1	2	1
1	22	0	0	0	0	2	20	36	35	44	49	26	19	15	9	1	2	1
1	23	0	0	0	0	3	20	36	38	45	49	26	19	15	9	1	2	1
1	24	0	0	0	0	3	20	39	39	46	49	28	19	15	9	1	2	1
...									...									...
101	97	0	0	0	0	9	73	120	127	99	70	50	24	17	8	2	2	1
101	98	0	0	0	0	9	73	120	127	99	70	50	24	17	8	2	2	1
101	99	0	0	0	0	9	74	121	128	99	70	50	24	17	8	2	2	1
101	100	0	0	0	0	9	74	123	128	99	70	50	24	17	8	2	2	1
101	101	0	0	0	0	9	74	123	128	99	70	50	24	17	8	2	2	1
101	102	0	0	0	0	9	74	123	129	99	70	51	24	17	8	2	2	1
101	103	0	0	0	0	9	74	124	129	100	70	51	24	17	8	2	2	1
101	104	0	0	0	0	9	74	125	129	101	70	51	24	17	8	2	2	1
101	105	0	0	0	0	9	75	125	130	101	70	51	24	17	8	2	2	1
101	106	0	0	0	0	9	75	127	130	103	71	51	24	17	8	2	2	1
101	107	0	0	0	0	9	75	127	131	103	71	51	24	17	8	2	2	1
101	108	0	0	0	0	9	75	130	133	103	71	51	24	17	8	2	2	1
101	109	0	0	0	0	9	76	131	134	104	71	51	24	17	8	2	2	1
101	110	0	0	0	0	9	76	132	135	104	73	51	25	17	8	2	2	1
101	111	0	0	0	0	9	76	132	136	104	73	51	25	17	8	2	2	1
101	112	0	0	0	0	9	76	132	136	104	73	51	25	17	8	2	2	1
101	113	0	0	0	0	9	76	132	136	104	73	51	25	17	8	2	2	1
101	114	0	0	0	0	9	76	133	136	105	73	51	25	17	8	2	2	1
101	115	0	0	0	0	9	76	133	136	106	73	51	25	17	8	2	2	1
101	116	0	0	0	0	9	76	135	137	106	73	51	25	17	8	2	2	1
101	117	0	0	0	0	9	77	135	139	106	74	51	25	17	8	2	2	1

Exhibit 6. Unsmoothed Parameter Estimates, File p653.pem

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	7	138	2	0	1	117	4	446.	173.70	1.397	542.	1078.	0.0	0.0
1	8	136	2	0	1	117	4	540.	145.73	1.676	785.	1209.	0.0	0.0
1	9	96	1	0	1	117	2	527.	100.17	1.502	0.	0.	0.0	0.0
1	10	62	1	0	1	117	2	403.	62.34	1.801	0.	0.	0.0	0.0
1	11	49	1	0	1	117	2	153.	49.00	1.818	0.	0.	0.0	0.0
1	12	20	1	0	1	117	2	79.	20.09	1.243	0.	0.	0.0	0.0
1	13	14	1	0	1	117	2	17.	14.04	1.835	0.	0.	0.0	0.0
1	14	10	1	0	1	117	2	44.	10.00	.709	0.	0.	0.0	0.0
1	15	2	1	0	2	116	2	1.	2.01	2.270	0.	0.	0.0	0.0
1	16	3	1	0	1	117	2	1.	3.00	1.608	0.	0.	0.0	0.0
...								...				...		
101	7	140	2	0	1	117	4	374.	172.05	1.424	738.	1123.	0.0	0.0
101	8	136	2	0	1	117	4	196.	140.52	2.131	893.	1525.	0.0	0.0
101	9	89	1	0	1	117	2	502.	90.42	1.531	0.	0.	0.0	0.0
101	10	74	1	0	1	117	2	635.	74.07	1.539	0.	0.	0.0	0.0
101	11	43	1	0	1	117	2	117.	43.46	1.627	0.	0.	0.0	0.0
101	12	23	1	0	2	116	2	50.	23.00	1.231	0.	0.	0.0	0.0
101	13	18	1	0	1	117	2	61.	18.00	2.039	0.	0.	0.0	0.0
101	14	4	1	0	1	117	2	21.	4.00	1.310	0.	0.	0.0	0.0
101	15	4	1	0	2	116	2	21.	4.00	.978	0.	0.	0.0	0.0
101	16	2	1	0	1	117	2	0.	2.00	3.600	0.	0.	0.0	0.0

Field Description:

(1) Replication number
(2) Class size
(3) Number of simulated fields found
(4) Model, 1=AR, 2=LAR (piecewise)
(5) Error code (0 & 1 imply convergence)
(6) Shift of number of cumulative wildcat well increments
(7) Number of well increments used by model
(8) Number of model parameters estimated
(9) Sum of squares error
(10) Unsmoothed estimate of ultimate number of fields
(11) Unsmoothed estimate of discovery efficiency
(12) Estimate of AR shift (gamma in LAR model)
(13) Estimate of joint (or cut) point (alpha in LAR model)
(14-15) Currently not used

Exhibit 7. Remaining BOE, Growth and Geometric Ratio by Replication, File p653.rem

Rep num	Remaining BOE	Growth BOE	Growth class 8-11	Geometric ratio mean	s.d.	n	Estimated ultimate numbers of fields Classes 5	6	7
1	131.55	1060.77	2501.8	1.565	.174	7	580.6	371.0	237.1
2	100.63	822.09	3973.0	1.515	.124	7	482.4	318.4	210.2
3	96.00	979.14	3087.2	1.541	.110	7	540.8	350.9	227.7
4	125.27	1020.10	2664.6	1.548	.192	7	552.1	356.8	230.5
5	100.05	1083.06	3167.1	1.573	.448	7	589.9	375.1	238.5
6	87.03	1014.13	3550.9	1.544	.122	7	548.1	355.1	230.0
7	107.80	946.60	3681.0	1.541	.111	7	531.4	344.9	223.8
8	91.10	1077.60	4247.9	1.562	.101	7	578.5	370.3	237.1
9	91.08	965.16	2755.4	1.536	.206	7	533.4	347.3	226.2
10	78.46	1032.06	2433.7	1.566	.265	7	569.9	364.0	232.4
11	35.53	828.00	2957.8	1.512	.167	7	480.0	317.4	209.8
12	213.54	1202.99	2236.4	1.587	.292	7	629.7	396.8	250.1
...			...		...				
86	87.67	1051.86	2968.2	1.553	.248	7	564.0	363.2	234.0
87	113.32	844.68	2840.4	1.508	.297	7	481.7	319.5	211.9
88	74.81	956.76	2266.8	1.542	.111	7	533.9	346.3	224.6
89	89.51	937.79	3231.8	1.539	.138	7	528.2	343.3	223.1
90	148.90	979.77	2665.5	1.541	.194	7	539.6	350.2	227.3
91	134.64	1024.55	1821.6	1.545	.221	7	554.8	359.1	232.5
92	145.23	1014.23	3016.1	1.565	.168	7	568.2	363.0	231.9
93	71.89	792.21	2489.9	1.499	.169	7	465.7	310.6	207.2
94	152.73	1099.29	3809.5	1.569	.213	7	586.7	373.9	238.3
95	160.13	892.73	1924.3	1.508	.249	7	494.9	328.2	217.6
96	78.44	928.36	2115.6	1.530	.367	7	518.0	338.5	221.2
97	71.24	936.43	2885.9	1.535	.198	7	523.9	341.2	222.3
98	113.58	1081.51	1834.8	1.567	.251	7	583.1	372.2	237.6
99	117.71	886.35	2069.1	1.533	.313	7	510.9	333.3	217.4
100	48.33	845.37	2779.7	1.519	.245	7	488.3	321.4	211.6
101	64.73	874.89	2598.6	1.507	.127	6	490.7	325.6	216.0

Exhibit 8. Remaining and Growth BOE Summary Statistics, File p653.fsd

ARDS v5.01 Date: 10/30/1997 Time: 15:39

FILE p653.fsd
Growth from year 1990 to 2010
Growth model:Onshore - Field
Model option: Best AR or LAR
BOE Scale: log 2 (6=1 MBOE)
Well increment: 100

Expected remaining field sizes-class by class averaged over 101 replications.
WARNING results may be affected by unusual reps.

Class	Ave Num of Flds	Ave MBOE
5	539.64	.71
6	241.85	1.43
7	89.49	2.86
8	5.89	5.60
9	2.97	11.50
10	.41	22.68
11	.04	46.72
12	.14	94.17
13	.01	178.16
14	.03	300.12
15	.01	578.02
16	.00	1559.72

		Remaining mm BOE Class Sizes	
	Rep	8- 16	5- 7
Q.10	14	59.602	1032.062
Q.50	42	107.796	902.748
Q.90	61	153.687	1024.548
Mean	65	107.950	982.716
80% T-mean		106.558	

Growth		mm BOE
	Rep	All Fields
Q.10	82	1989.580
Q.50	79	2826.610
Q.90	71	3952.820
Mean	97	2888.518
80% T-mean		2866.539

For means, replication is one closest to mean
For quantiles, replication based upon large size class estimates

Exhibit 9. Estimated Ultimates, File p653.ult

ARDS v5.01 Date: 10/30/1997 Time: 15:39

PLAY p653
Model option: Best AR or LAR
BOE Scale: log 2 (6=1 MBOE)
Well increment: 100
Type of fields: Oil & Gas
Growth from year 1990 to 2010
Growth model: Onshore - Field

Quan tile	Class	Eff	Ult Flds	Grown Flds Fnd	Actual Flds Fnd	-----BOE x 10E6--- Remaining	Ultimate
10	5	.000	517.3*	0.	0	365.8	365.8
10	6	.000	337.7*	0.	158	482.1	482.1
10	7	1.554	220.4*	139.	130	232.8	630.2
10	8	2.013	131.4	128.	124	19.2	736.2
10	9	1.531	102.9	101.	82	22.4	1183.7
10	10	1.959	71.0	71.	74	.0	1610.1
10	11	1.334	38.0	38.	36	.0	1775.4
10	12	1.564	24.1	24.	16	12.2	2272.3
10	13	1.767	17.0	17.	14	.0	3028.7
10	14	.684	9.0	9.	7	.0	2701.1
10	15	2.270	2.0	2.	2	5.8	1161.8
10	16	3.600	2.0	2.	3	.0	3119.4
Total			1472.9	531.	646	1140.2	19066.9
* Geometric ratio = 1.53							
50	5	.000	525.7*	0.	0	371.7	371.7
50	6	.000	341.8*	0.	158	487.9	487.9
50	7	1.528	222.2*	153.	130	197.9	635.4
50	8	1.709	134.3	126.	124	46.7	752.6
50	9	1.573	93.9	91.	82	33.0	1079.3
50	10	1.812	75.0	75.	74	.0	1700.9
50	11	1.713	45.0	45.	36	.0	2102.5
50	12	1.364	19.2	19.	16	17.0	1806.2
50	13	2.152	18.0	18.	14	5.3	3212.2
50	14	.583	7.0	7.	7	.0	2100.8
50	15	.807	3.0	3.	2	5.8	1739.8
50	16	1.608	3.0	3.	3	.0	4679.2
Total			1488.1	540.	1292	1165.3	20668.4
* Geometric ratio = 1.54							
90	5	.000	598.3*	0.	0	423.1	423.1
90	6	.000	380.7*	0.	158	543.4	543.4
90	7	2.069	242.2*	131.	130	318.0	692.6
90	8	1.350	150.7	130.	124	115.7	844.0
90	9	1.570	97.0	95.	82	22.9	1115.1
90	10	1.898	69.0	69.	74	.0	1564.8
90	11	1.494	42.0	42.	36	.0	1962.3
90	12	1.131	22.2	22.	16	15.1	2086.8
90	13	2.643	15.0	15.	14	.0	2672.4
90	14	1.052	10.0	10.	7	.0	3001.2
90	15	.970	4.0	4.	2	.0	2312.1
90	16	2.338	1.0	1.	3	.0	1559.7
Total			1632.0	519.	1938	1438.2	18777.5
* Geometric ratio = 1.57							

Exhibit 10. Constant File p653.con and Descriptors (file grcon.dat)

File p653.con follows:

```
p653        1 1 1 0  4627   646 1 11665 11700    42362.   100 2  9034  16
1 1 1990 2010   7   7  16 3 1  5  14  42  61  65
```

Description of the elements in file p653.con.
grcon.doc documents the fn.con file used by all Fortran programs in ARDS 5.00.

Cols.	Format	Description	Program
1-10	a10	play name	aformat.for
11-12	i2	oil/gas code (1=O&G, 2=O, 3=G)	
13-14	i2	input units of oil code (1=thous bbl, 2=mill bbl)	
15-16	i2	input units of gas code (1=millions cu ft, 2=billions cu ft)	
17-18	i2	input units of area code (0=acre, 1=sq km, 3=sq mi)	
19-24	i6	random number seed-missing dates	
25-30	i6	number of fields	
31-32	i2	wells 1=total exploratory (Lahee 2-5) 2=new field wildcats (Lahee 5)	amerg.for
33-38	i6	cumulative wildcat-last	
39-44	i6	number of wells processed-rounded up to next well increment	adtable.for
45-54	f10.0	play size (sq.km.)	
55-60	i6	well increment	
61-62	i2	scale for size classes 1=log base (2) scale=0.0593 2=log base (2) Class 6=1 MBOE, usual 3=log base (4) Class 6=1 MBOE 4=user defined size classes	
63-68	i6	random number seed-growth model	agrow.for
69-72	i4	largest size class-grown fields all data present	
73-74	i2	onshore(1), offshore(2),no growth(0)	
75-76	i2	field(1), reservoir(2) growth	
77-81	i5	year-grow fields from	
82-86	i5	year-grow fields to	
87-90	i4	average modal class	
91-94	i4	beginning class size for nonlinear estimation	aest.for
95-98	i4	ending class size for nonlinear est	
99-100	i2	model option, AR(1), LAR(2), best(3)	
101-102	i2	estimate small fields (1=y,0=n)	
103-105	i3	beginning class size, small field est	
106-109	i4	replication for q10 remaining BOE	aresult.for
110-113	i4	replication for q50 remaining BOE	
114-117	i4	replication for q90 remaining BOE	
118-121	i4	replication closest to mean rem BOE	

APPENDIX A. EXAMPLE FROM SUPERPLAY 653

```
aformat

ARDS v5.01
Date: 09/09/1997   Time: 20:27

Program AFORMAT.FOR reformats the field file and
 estimates missing month, day

Enter play name - no extensions, i.e., p653 (9 char max)
p653

Field file data:
             3-digit year, i.e. 938, in ID
             Field name
             Gas (if used)
             Natural gas liquid (if used)
             Oil (if used)
             Area
             Date of discovery yyyy/mm/dd

  The format is: (4x,i3,4x,a25,49x,i10,23x,i10,23x,
                  i10,15x,f6.0,3x,i4,1x,i2,1x,i2)

 It is assumed the field file is named p653.fld
 The reformatted output file is p653.ytw
If OK, hit Enter, else Break, Rename, and Restart

The current year in this computer is: 1997

Type of fields to include:
    1-Oil & Gas
    2-Oil only (Non assoc gas:oil < 20mcf:1 bbl)
    3-Gas only
  Natural Gas Liquid (NGL) is coverted to bbl and counted as oil
1
 Enter units
  Oil, t=thousands of barrel, m=millions of barrel
   Note: Units of NGL assumed to be same as oil
t
  Gas, m=millions cu. ft., b=billions cu. ft.
m

To estimate missing month/day (if necessary),
 enter random seed [1 to 32767] or 0 (to have computer choose)
4627
 Field AREA in Acres (Nehring convention)? y/n
y

  646 fields written to output file p653.ytw

Output file is p653.ytw
It contains:
 Discovery YR, MON, DAY, BOE (thousands bbl), Area (sq km),
  % Ultimate Gas, NGL, Oil & Field Name

The next program AMERG.FOR, merges fields with wells:
  To run, enter AMERG
Stop - Program terminated.
```

```
[W]C:\My Documents\ards\data>amerg


ARDS v5.01
Date: 09/09/1997   Time: 20:28

 Program AMERG.FOR-Merge well & field files,
   estimate missing areas-function AREST
 Enter name of play - no extensions, i.e. p653
p653

 It is assumed that the reformated Nehring file is named p653.ytw
 The input well file is p653.wel
 The merged field-well output file is p653.dtw
 The year-cumulative wildcat well table is p653.tcw
 The constant (input/output) file is p653.con

** If OK, hit Enter, else Break, Rename, and Restart

Pause - Please enter a blank line (to continue) or a DOS command.


Type of Wells to be Processed
  1 = Total Exploratory Wells (Lahee classes 2-5)
  2 = New Field Wildcats (Lahee class 5)
 Enter 1 or 2
1

There are  71 missing areas
Model used is: ln area=  .4911 +  .4639 ln BOE
    R2=  .49  Std Dev=       .6599 n=   575

 Use these calculated values? y/n
y

Merged field-well file is p653.dtw        It has  646 fields
 File contains: Cumulative wildcat well
                BOE (millions of barrels)
                Area (sq. km.)
                Year, month, day of discovery
                % Gas, NGL, Oil of ultimate recovery
                Field name

 First discovery at     1 wells, on 1907/02/14
 Last discovery at  11665 wells, on 1989/10/24

 Next program ADTABLE.FOR generates discovery table & basic  stats
 To run enter ADTABLE
Stop - Program terminated.
```

```
[W]C:\My Documents\ards\data>adtable


ARDS v5.01
Date: 09/09/1997   Time: 20:28

Program ADTABLE.FOR creates discovery table, file & basic stats
 Enter name of data, i.e. p653 (No extension)
p653

 It is assumed the well/field file is named p653.dtw
  and data (separated by spaces or ,) are:
  Wells, boe, area, year, mon, day of discovery

 Discovery table, disc. file, basic stats, and constants
   will be named p653       with extensions:
     .dt
     .dp
     .sta, and
     .con respectively.
  A print file is adtable.prn.

   ** Existing files with these names will be destroyed **
 If OK, hit Enter, else Break, Rename, and Restart

Pause - 1


Enter play (or basin) size (sq. km.)
42362.

ENTER well increment - 100 is usual
100

ENTER a,m, or d
  a - to use all wells
  m - to specify maximum well number
  d - to specify maximum date
a

Specify scale (size class):
         1=log base 2(0.005930)
         2=log base 2 (usual)
         3=log base 4
         4=user defined
2

Next program is ASAREA.FOR
  which yields regression smoothed Average Area by Class.
  To plot this smoothed area (& raw area) vs BOE, run Systat
  macro: ASAREA.CMD. Type macro, then submit asarea
Stop - Program terminated.
```

```
[W]C:\My Documents\ards\data>asarea

ARDS v5.01
Date: 09/09/1997   Time: 20:36

Program ASAREA.FOR
Creates smoothed areas using the model:
 log(area)=b0+b1*log(ave boe)+b2*log(ave boe)^2
 Enter name of data, i.e. p653 (No extension)
p653
 Convergence : SSE=  6.873863743064701E-001  Iterations   6

Plot smoothed areas using Systat Macro ASAREA.CMD
To run ASAREA, type macro, then submit asarea
Next Fortran program is AGROW.FOR
Stop - Program terminated.
```

ARDS v5.01 Date: 10/30/1997 Time: 12:33

FILE p653.fsd
Growth from year 1990 to 2010
Growth model:Onshore - Field
Model option: Best AR or LAR
BOE Scale: log 2 (6=1 MBOE)
Well increment: 100

Expected remaining field sizes-class by class averaged over 101 replications.
WARNING results may be affected by unusual reps.

Class	Ave Num of Flds	Ave MBOE
5	539.64	.71
6	241.85	1.43
7	89.49	2.86
8	5.89	5.60
9	2.97	11.50
10	.41	22.68
11	.04	46.72
12	.14	94.17
13	.01	178.16
14	.03	300.12
15	.01	578.02
16	.00	1559.72

Remaining MBOE

		Class Sizes	
	Rep	8- 16	5- 7
Q.10	14	59.602	1032.062
Q.50	42	107.796	902.748
Q.90	61	153.687	1024.548
Mean	65	107.950	982.716
80% T-mean		106.558	

Growth MBOE

	Rep	All Fields
Q.10	82	1989.580
Q.50	79	2826.610
Q.90	71	3952.820
Mean	97	2888.518
80% T-mean		2866.539

For means, replication is one closest to mean
For quantiles, replication based upon large size class estimates

90	16	2.338	1.0	1.	3	.0	1559.7
Total			1632.0	519.	1938	1438.2	18777.5

* Geometric ratio = 1.57

```
[W]C:\My Documents\ards\data>agrow

ARDS v5.01
Date: 10/30/1997   Time: 20:47

Program AGROW.FOR grows fields
Program produces  101 discovery tables (replications)

 Enter name of data, i.e. p653
p653
    Input files must be named p653      with extensions:
       .con, constants (input/output file)
       .dp,  well/field
       .stb, basic stats file
    Output files will be named p653      with extensions:
       .dpr, grown fields for 1st replication
       .dtr, discovery table files; 1 per replication
       .gro, simulated growth for each replication
     IF OK PRESS ENTER

Pause - 1



Play size=    42362. Max wells= 11700 Scale code=  2

 Growth option, y/n?
y

Enter random seed [1 to 32767] or 0 (to have computer choose)
9034
Growth model (enter):
  1-US onshore
  2-W.Gulf Mexico offshore
  3-World Oil
1
 Field (1) or Reservoir (2) growth?
1
Grow fields to --  enter 4 digit year
2010

Enter year (4 digits) to begin growth
 Normally this is year of last update
1990

Largest Size Class Containing at Least One Field: 17
Largest Size Class with Data Present in All Classes 16

The next program is AEST.FOR
Stop - Program terminated.
```

```
[W]C:\My Documents\ards\data>aest


ARDS v5.01
Date: 10/30/1997   Time: 20:48

Program AEST.FOR estimates A-R or linear AR model parameters

 Enter name of data, i.e., p653
p653
 Model: AR(1), Linear-AR(2), Best model(3)
3

Enter beginning and ending class size for estimates.
 Beginning is typically the modal class size M or M+1 of grown distn
 Ave modal class =  7
 Largest size class with data present in all reps = 16
7,16

Last replication used 101
Next program is ARESULT.FOR
Stop - Program terminated.
```

```
[W]C:\My Documents\ards\data>aresult

ARDS v5.01
Date: 10/30/1997   Time: 20:49

Program ARESULT.FOR estimates remaining BOE for each rep.

Enter name of data, i.e. p653
p653
 Estimate remaining small fields? y/n
y
Enter geometric ratio or 0 to have it computed
  Computed geometric ratio bounded between 1 and 2
0
Enter minimum size class for small field estimation
 Note, this is usually 1 to 3 class sizes below the mode.
5

Last replication used  101

See file p653.fsd        for field size distn & quantile est
See file p653.ult        for ultimates on quantile est

Stop - Program terminated.
```