

Interim Report: Development of Resistively
Heated Diesel Particulate Trap/Regeneration Systems

by

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I. Technical Approach and Current Industry Efforts

New vehicle and engine emission standards for future model years have stimulated the development of advanced control systems for Diesel particulate emissions from light and heavy duty Diesel vehicles.[1] The standards which new Diesel vehicle and engine manufacturers are now challenged to meet are listed in Table 1.

In past years, development has dealt largely with an aftertreatment control technology commonly known as the "trap oxidizer" or the "catalyzed trap oxidizer" (CTO). The common CTO is a means of trapping or filtering the particulate matter in Diesel vehicle exhaust and eliminating it in place by thermal oxidation, commonly referred to as regeneration. These devices first appeared four years ago on one passenger vehicle model in the United States. Although production of CTOs is presently suspended, there are approximately 30,000 trap oxidizer-controlled Diesel vehicles in customer use.[2]

Heavy-duty trap system development programs are in progress throughout the world sponsored by almost every Diesel vehicle and engine manufacturer. Many of these programs are targeted to meet 1991 and 1994 truck and bus standards, while others are aimed at retrofit system development for buses and some off-highway vehicles. Some heavy-duty manufacturers will conform to the 1991 heavy-duty truck standards without traps, especially if the sulfur content in Diesel fuel is reduced. However, trap oxidizers may be used in limited instances in 1991. While almost every manufacturer has a trap development program, they are also focusing a share of their efforts on engine modifications, advanced turbocharging and even flow through catalytic converters.[3]

Durability and packaging problems led to the suspension of the only production trap systems this past model year. As such, alternative control systems and improved trap oxidizer systems are needed for Diesels to meet the current light-duty and future heavy-duty particulate emission standards. Problems with the developing traps, which are generally either wallflow or porous foam ceramic substrates, include inadequate surface area, quick backpressure buildup and/or nonuniform soot distribution and regeneration. Proper catalytic coating can alleviate the regeneration and surface area problems to some extent, but trapped ashes from lubricating oil can decrease catalytic activity drastically.[4]

Table 1

New Vehicle and Engine Emission Standards

	<u>LDV (gpm)</u>			<u>LDT (gpm)</u>			<u>HD (g/BHP-hr)</u>		
	<u>HC</u>	<u>NOx</u>	<u>Part.</u>	<u>HC</u>	<u>NOx</u>	<u>Part.</u>	<u>HC</u>	<u>NOx</u>	<u>Part.</u>
1988-9	0.41	1.0	0.2	0.8	1.2/1.7[1]	0.26[2]	1.3	10.7	0.6
1990	0.41	1.0	0.2	0.8	1.2/1.7	0.26	1.3	6.0	0.6
1991-3	0.41	1.0	0.2	0.8	1.2/1.7	0.26	1.3	5.0[3]	0.25[3]/ 0.10[4]
1994+	0.41	1.0	0.2	0.8	1.2/1.7	0.26	1.3	5.0	0.10[5]

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- [1] Vehicles over 6,000 lbs GVW remain at 2.3 gpm NOx until 1990. Standards of 1.2 gpm apply to LDTs up to and including 3,750 lbs. loaded weight; 1.7 gpm standard applies to LDTs equal to and over 3,751 lbs. loaded vehicle weight. Emissions averaging may be used to meet this standard provided that trucks produced for sale in California or designated high-altitude areas may be averaged only within each of those area. Diesel and gasoline-fueled engine families may not be averaged together.
- [2] Emissions averaging may be used to meet this standard provided that trucks produced for sale in California or designated high-altitude areas may be averaged only within each of those areas.
- [3] Emissions averaging may be used to meet this standard, but these emissions may not be averaged with HD gasoline engine emissions. Averaging is restricted to within useful life subclasses (see below). Also, averaging is restricted regionally--the two regions are California and the other 49 states.
- [4] For urban bus engines, the standard is 0.10 g/BHP-hr--particulate averaging is not allowed with this standard, but emissions from these engines may be used in NOx averaging.
- [5] Emissions averaging may be used to meet this standard. However, averaging is restricted to within useful life subclasses (see below). Also, averaging is restricted regionally--the two regions are California and the other 49 States. Emissions from engines used in urban buses may not be included in the averaging program.

Full useful life is established for 1985 and later defined as:
 Light heavy-duty (under 19,500 lbs. GVWR) = 8 yrs/110,000 miles
 Medium heavy-duty (19,500-33,000 lbs. GVWR) = 8 yrs/185,000 miles
 Heavy heavy-duty (over 33,000 lbs. GVWR) = 8yrs/290,000 miles

The concept of resistively heated Diesel particulate traps for improved regeneration efficiency and uniformity has been evaluated by EPA over the past two years.[5] It was found that although the regeneration characteristics can be optimized, these conditions also must be optimized with improved filtering surface area, and durability. The resistively heated trap system evaluated was a doped porous silicon carbide tubular fiber element, produced by the Fogarty Division of Coloroll, plc. The idea was to have the trapping media be a resistive element so that when regeneration was desired, the particulate could be heated directly by resistively heating the trap media. In this way, intermediate heat transfer losses of conventional oxidation methods of heating air to heat the particulate or heating wires to heat the particulate would be avoided. This work resulted in the identification of a resistive material that could both trap Diesel particulate (at efficiencies of 70 percent) and be uniformly and completely regenerated. On the downside, rapid backpressure buildup with this system forced regeneration frequency to occur every 15 to 20 miles.

Among the manufacturers, little has been made public in the area of resistively heated traps and nothing has been published. Various manufacturers have, however, reported results of conventional CTO development programs over the past year at the SAE Congress and other public forums. On the light-duty side, FEV and Volvo published a paper this year on the development of a system for the Volvo 760 turbo-Diesel vehicle. This system has a conventional honeycomb wallflow trap, but also and has a modified double-walled manifold, portliners and intercooler bypasses.[6] With this system, the particulate emissions can be lowered below the 0.2 g/mi standard over the FTP without unacceptable deterioration of other pollutant emissions and vehicle driveability. Problem areas which still remain include temperature control and thermal resistance as they relate to trap durability. At low temperatures and low speeds during urban cycle testing the accumulated soot mass in the trap can become too high and cause cracks and partial melting of the trap subsequently during accelerations. Also at low temperatures starting problems were observed. Mercedes-Benz also published a paper of a light-duty trap development program using their 5-cylinder engine.[7] This system employs a pressure wave supercharger which shows advantages in driveability, particular under high altitude conditions. However, in combination with a particulate trap, most of the advantages of the pressure wave supercharging disappear even with a particulate trap reduced in size by 50 percent.

On the heavy-duty side, the General Motors Corporation published a report of trap development aimed at meeting the 1991 and 1994 particulate emission standards.[8] The GMC system is a conventional cordierite ceramic trap with a

burner-bypass system. This system shows promise toward achieving 290,000-mile durability though only 100K mile durability was simulated, and the system does not meet both 1991 particulate and NOx emission standards simultaneously. If the 1991 NOx standard of 5.0 g/BHP-hr is met, the lowest particulate emission rate achieved is roughly 0.3 g/BHP-hr, i.e., 20 percent over the 1991 standard and 300 percent over the 1994 standard. Among other heavy-duty efforts, Cummins is currently evaluating a resistively heated trap aimed at meeting the 1991 and 1994 particulate standards, a modified Coloroll system, and have yet to report their experience with it. Southwest Research Institute has also proposed an evaluation (see Appendix) of a modified Sohio silicon carbide or other high-temperature resistant trap as part of work to be performed by the Consortium of Heavy-Duty Diesel Manufacturers.[9]

II. Technical Progress

The resistively heated trap material suppliers dealt with can be sorted into two categories, those who have either sent EPA material samples for evaluation or have done some evaluation themselves, and those who have either not shared with EPA the results of their development work or have not done much development recently. The "haves" include Coloroll, Sohio, Duriron, Hi-Tech Ceramics and Aker Industries, and the "have nots" include NGK, Corning, Matsushita, most heavy-duty manufacturers and others. Suppliers who plan either development or evaluation in cooperation with EPA in the future include Selee, Hi-Tech Ceramics and possibly Sohio, Camet and Duriron. These latter programs will be discussed in the next section.

A. Coloroll (Low Density)

A complete description of the first and second generation Coloroll trap system evaluation is contained in reference [5]. Efficiency tests were run on the new Coloroll filters which are two-thirds the weight of the original filters (i.e., more porous). Load-up time is about the same since these filters are still surface loaders (rather than bulk loaders) and more soot passes through. Baseline 0.45 g/mi particulate was reduced to 0.23 g/mi for an efficiency of roughly 50 percent. Regenerations were performed efficiently with similar results as the previous samples.[10]

B. Coloroll (Bypass Regeneration)

Tests were run with the original Fogarty can equipped with a baffle plate and dividers to bypass exhaust flow through two unpowered filters while the third (isolated) filter is regenerated. No improvements in regeneration efficiency or regeneration time were obtained. At low speed and idle, very little heat is available to enhance the burn. At high speeds, backpressure increases in spite of the regenerating filter, and

the higher amount of exhaust flow through the baffle plate cools the burning filter down below soot ignition temperatures. A baffle plate with smaller holes, which would allow only 1 or 2 cfm maximum exhaust flow, may improve regeneration. The basic Coloroll system still exhibits problems in not having adequate surface area to lower regeneration frequency and in unknown durability of the ceramic-to-metal interface even when intermediates such as steel wool matting are used.

C. Sohio

Sohio Engineered Materials, Inc. (formerly Carborundum) previously sent EPA several 2-inch thick 5.25-inch diameter silicon carbide foam "doughnuts" (1.75-inch inside diameter) for evaluation. These hollow cylinders were quite heavy, over 600 g each (0.95 g/cm^3), and as such required too much energy (over the 2.5 KW power supply capacity) to heat to regeneration temperatures. Three doughnuts were sandwiched together in our test rig for initial EPA evaluation (see Figure 1), to get the filtering capacity that these Sohio doughnuts exhibited when tested previously by Southwest Research Institute.[11] EPA was at first more concerned with the resistance problems which were anticipated with this design. It was believed that, even when steel wool intermediates were used between doughnuts, it would be better to have just one 6-inch thick doughnut to minimize the number of material interfaces at two. However, in the interest of also reducing energy requirements, EPA asked Sohio to significantly increase the inside diameter such that outside surface area is preserved but the filter mass is reduced. A drawing of the filter material configuration requested is shown in Figure 2. Sohio has yet to produce such a sample for EPA evaluation but is still committed to doing so.

Figure 1

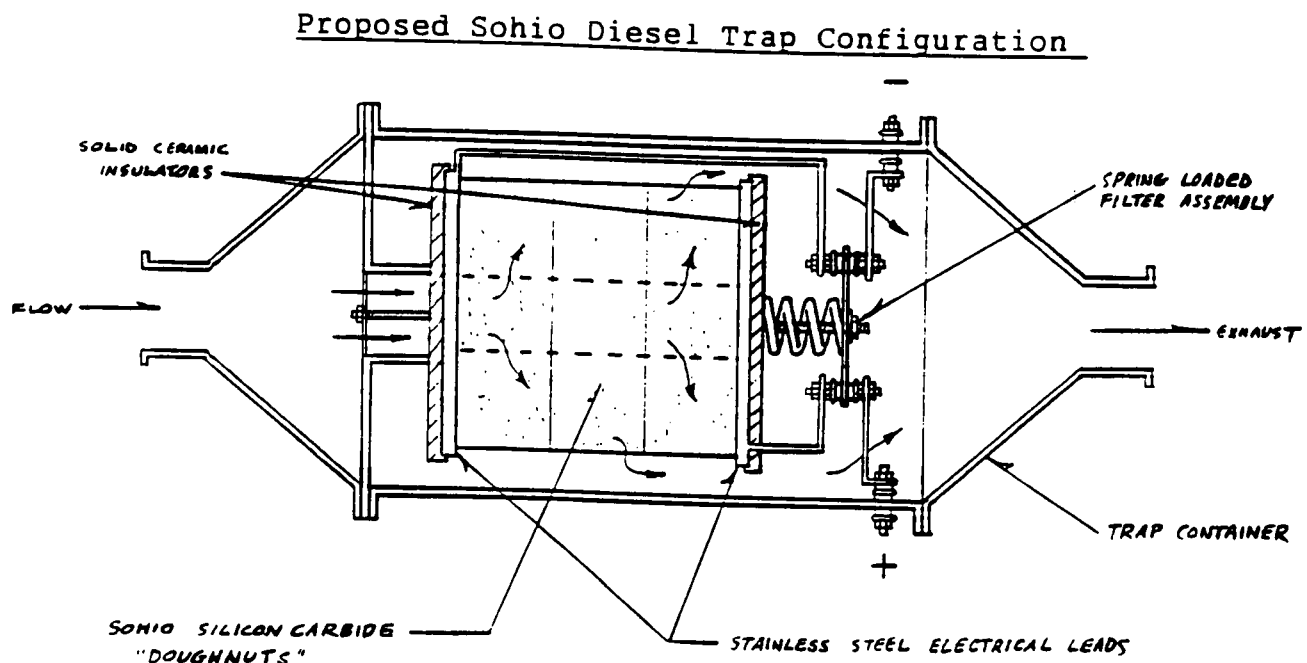
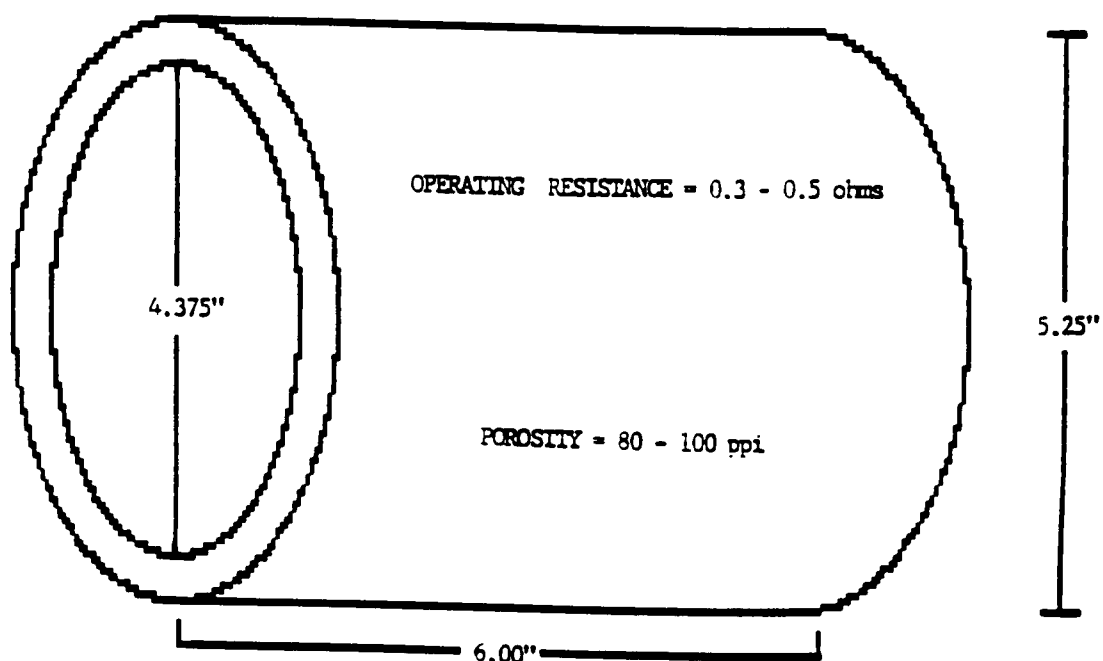


Figure 2

Sohio Resistive Diesel Particulate Filter Element



Particulate collection efficiency and loading tests have been carried out on the Sohio silicon carbide foam samples. Silicon carbide foam samples with filter porosities of 45, 60, 80 pores per linear inch (ppi) have been received from Sohio at Ricardo Consulting Engineers, plc., EPA's Diesel trap evaluation contractor.

The Sohio silicon carbide foam examples exhibit a relatively poor maximum collection efficiency of 30 percent, with the larger pore-sized samples showing signs of particulate "blow off." Thermogravimetric analysis of the particulate samples shows that the Sohio Diesel particulate filter element does not affect the makeup of the filtered particulate carbon content.[12]

Tests using a typical vehicle 12-volt battery and the 2-inch x 3-inch x 1-inch Sohio 80 ppi silicon carbide foam sample shows that a material surface temperature rise of 135°C (275°F) can be achieved in about 10 seconds. Wire wool and thin (about 10mm) stainless steel plates were used to make the electrical terminations. Current measurement was attempted but the levels involved exceeded the full-scale range of 75 A of the meter. Further tests using a partially discharged 6-volt vehicle battery had allowed current measurements to be made and the electrical resistance of the sample to be determined as 0.055 ohms with electrical contacts on the 2-inch x 1-inch

faces, i.e., oriented for maximum resistance. This level of resistance was considered to be too low for practical particulate trap-application (i.e., current requirements for a given voltage are beyond the capacity of conventional power supply sources), but because of the briefness and simplicity of the tests, the resistance level measured may not accurately reflect the inherent material characteristics.

D. Duriron

EPA's initial contact at Duriron retired and his successors do not appear to be aggressively pursuing any major development in resistively heating as yet. Initial evaluation of their material showed a need for improved electrical properties. Duriron is currently supplying Ricardo with some porous (nonconductive) cordierite samples that have solid conductive silicon carbide coatings.

A sample of the Duriron non-conductive foam with integral downstream membrane was tested. Results showed a particulate collection efficiency in the region of 40 percent and a back pressure rise rate between that of the standard Coloroll element and the Sohio 80 ppi SiC foam. This collection efficiency may be good for low ppi samples, but not so good for high ppi samples. The Duriron material is believed to be low ppi (e.g., about 50 ppi) but the effect of the membrane on overall porosity and soot collection is unknown at this time.

E. Hi-Tech Ceramics

The Hi-Tech Ceramics material was initially evaluated in a 1-inch thick by 2-inch diameter sample. Their material was subsequently evaluated for resistive heatability by clamping a 6-inch long sample between two 1/2-inch thick solid stainless steel disc-shaped electrical leads, which are in turn sandwiched between two solid ceramic insulators such that all current is dissipated through the porous SiC sample. Current and voltage were measured as power was supplied to the heater assembly. Initially, the sample was weighted to determine material density (equal to 0.285 g/cm³) which is roughly 20 percent less dense than the initial smaller sample.

The evaluation showed that this material displays a negative temperature coefficient since resistance decreased with increasing temperature. Exact filter temperature measurements were not obtained due to lack of an optical instrument which operates in the range of filter temperatures experienced during thermal cycling of the sample. Resistance approached 1.0 ohm at very low power settings and decreased to roughly 0.5 ohms at power settings over 1500 watts (maximum current loadings). Current applied to the heater did not remain stable at a given setting and decreased 1 to 2 amps before stabilizing. Voltage drifted down 20 to 25 percent from the preset loading as did the initial sample. The electrical properties observed through the thermal cycling of the material are shown in Table 2.

Table 2

Electrical Properties of Heated
Hi-Tech Ceramics Silicon Carbide Foam

<u>Test Run</u>	<u>Initial Voltage (volts)</u>	<u>Stabilized Voltage (volts)</u>	<u>Current (amps)</u>	<u>Power (watts)</u>	<u>Heated Resistance (ohms)</u>
1	21.8	17.7	20.5	363	0.86
2	25.5	20.4	28.7	585	0.71
3	26.5	22.8	38.0	866	0.60
4	28.3	24.4	48.0	1171	0.51
5	29.6	26.8	58.5	1568	0.46
6	18.0	--	33.5	603	0.51
7	10.3	--	28.5	465	0.54
8	15.0	--	27.0	405	0.56
9	14.4	--	24.5	353	0.58
10	12.0	--	19.5	234	0.60

Contrary to the initial sample results, the current drift did not increase with increasing temperature. Also, perhaps because the sample was deformed as-received, further material deterioration was observed with continued thermal cycling. The material glowed orange-hot at current loadings above 30 amps, but the glow was not uniform and tended to be concentrated along the cracks in the material. Length-wise cracks developed on the outer surface of the material, but the sample remained intact as one piece. The cracking may also have been exacerbated by the use of a rigid clamp to hold the heater assembly together rather than a spring loading assembly which would compensate for the different expansion rates of the ceramic and metal components. The negative temperature coefficient (NTC) characteristic of the material is seen by comparing test 1 with test 10 in Table 2. After the material had been heated in tests 1 through 9, the low power resistance was 0.60 ohms compared to 0.86 ohms when the material was "cold."

A tubular cracked sample of the Hi-Tech SiC ceramic 45 ppi foam was shipped to Ricardo for further evaluation. Although fractured, a sample 75 x 50 x 25 mm was machined from the piece and characterization tests were carried out.[13] Graphs of backpressure rise versus loading rate for the Hi-Tech and other samples, as tested by Ricardo, are contained in the Appendix. The particulate loading tests showed a collection efficiency of 5-20 percent at the standard engine condition (medium speed and load) used throughout the Ricardo characterization tests. Tests at a lower engine speed to reduce the exhaust gas flow rate through the sample resulted in collection efficiencies of 10 to 30 percent. Backpressure rise rate was insignificant indicating that particulate was regularly being "blown off"

during the test period. This was readily apparent when a jet of air directed at the loaded foam sample removed from the test installation resulted in clouds of particulate dust being emitted from the sample. Subsequent electrical tests on the Hi-Tech sample using a typical 12-volt vehicle battery indicated an electrical resistance of about 6 ohms resulting in little resistive heating of the sample.

EPA now proposes to build a container for further evaluation of the Hi-Tech Ceramics material as a Diesel particle trap/regenerator. The proposed testing apparatus is similar to the container shown in Figure 1. Testing shall include determinations of filter efficiency, backpressure rates and regeneration efficiency on the EPA's Mercedes 300D test vehicle. If feasible, our Diesel evaluation contractor (Ricardo) shall fabricate the proposed container and perform initial evaluations prior to more detailed evaluation of the final system configuration at the EPA Motor Vehicle Emission Laboratory.

F. Aker Industries

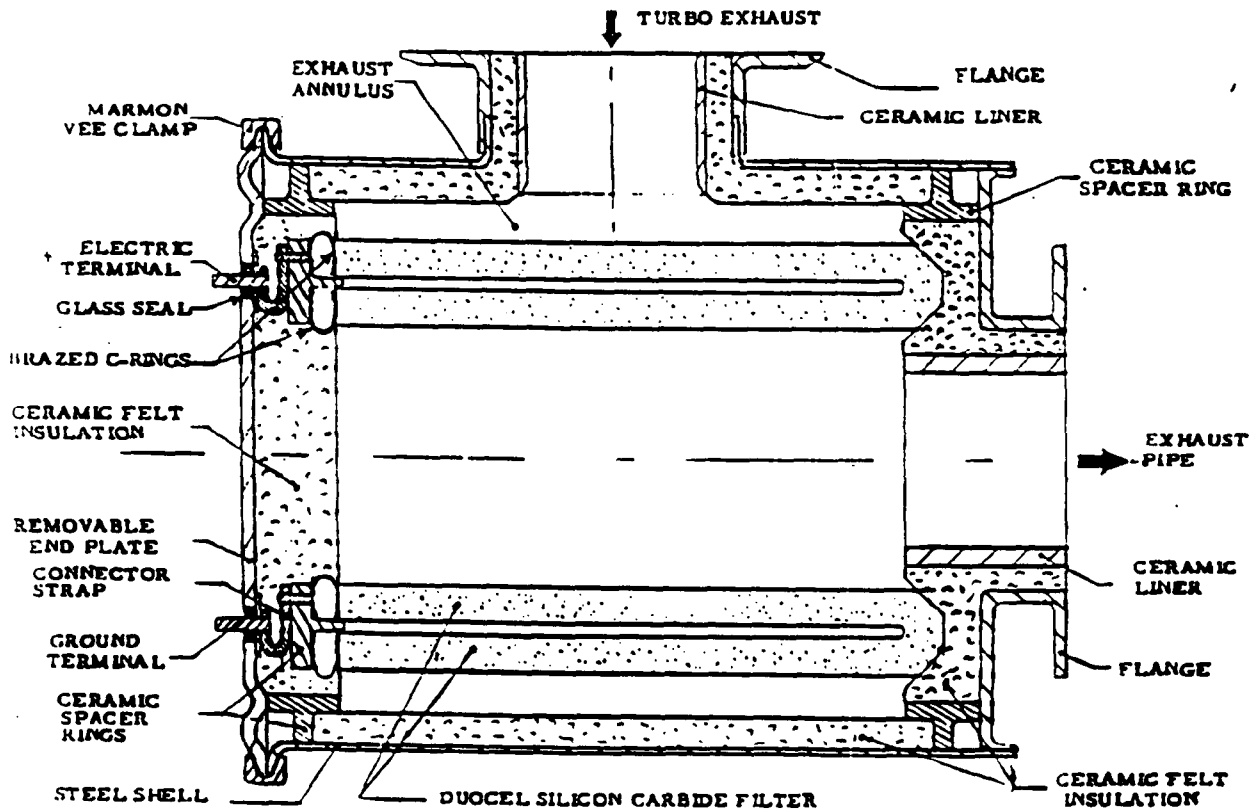
Aker Industries had recently been formed to exploit commercial markets for advanced ceramic materials. Dr. Benson, the CEO, had previously been associated with Energy, Research and Generation, Inc. (ERG) who supply predominantly defense establishments with specialized materials.

ERG had been involved with particulate traps in the mid-1980s and had supplied electrically regenerable silicon carbide foam traps to various engine manufacturers for evaluation. Their trap design, shown in Figure 3, included a foam with a variable density so that electrical terminations could be made by brazing metal contacts onto solid silicon carbide.[14] This avoided differential thermal expansion problems between the metal contact and ceramic, which was another problem experienced in the previous evaluation of the Coloroll trap, since the solid silicon carbide and the brazed metal contact presented insignificant electrical resistance compared to the main part of the silicon carbide element and were thus not resistively heated. Tests with this trap design showed that, with a 100 ppi foam about 40 mm thick, particulate collection efficiencies were only 30-35 percent.

Following this work a non-rigid pleated fiber mat filter design was developed. A tubular construction was used with an outside diameter of 6 inches, a 0.02-inch wall thickness and a

Figure 3

Aker Industries Diesel Trap Configuration



length of 8 inches. A 10mm diameter silicon carbide fiber was used in the matted material. Tests were conducted on a Mercedes-Benz 190D vehicle over 492 miles. An average trapping efficiency of 91 percent was achieved and roughly 50g of particulate was collected before each regeneration which was carried out by placing the filter in a kiln and heating to 980°C (1800°F). Typically pressure drop across the filter increased from 55 mbar for the cleaned condition to 90 mbar for the loaded condition. The ratio of mass of particulate collected at a given backpressure to the mass of the filter was approximately 1.00 compared with only 0.10 for the Coloroll material.

Aker Industries are currently working on manufacturing a silicon carbide non-rigid fiber mat filter of pleated tubular construction. The filter, 18 inches long, will have an inner diameter of 5 inches with 1-1/2 inch deep pleats giving a surface area enhancement factor of 5.2. The filter will be corrugated in the axial direction and will be supported by metal rings at various intervals along its length. It was claimed that the pleated structure would minimize radiative

heat loss during regeneration as heat would mainly be radiated from one pleat to another. In addition, Aker Industries explained that a non-rigid fiber mat construction would not catastrophically fail by cracking as is the case in a foam structure which behaves as a monolith in its failure mechanisms.

Electrical terminations will be similar to those used for the foam design. Ricardo currently lacks enough EPA contract funding for purchasing additional material samples for materials characterization tests. Aker Industries stated that it would be manufacturing filters for clients later this year and that it may be possible to supply Ricardo with some sort of free sample at that time.

Aker Industries described the manufacturing process they employed for making silicon carbide. A textile precursor is used to manufacture a vitreous carbon copy which is then infused with silicon to make a 100 percent dense slightly silicon rich of stoichiometric beta form of silicon carbide. This results in a material with a fine grain size giving it improved durability and a positive electrical resistance temperature coefficient. By making the fibers 100 percent dense, oxidation of the material under high temperatures is reduced to surface oxidation only. Aker Industries noted that for durability, the temperature of the material during use should be maintained below 1200°C (2200°F) and that contact with vanadium and alkali metals should be avoided as these metals react with the silicon carbide by ion exchange. Aker also claims that their manufacturing process is much less costly than the Coloroll process, which utilizes expensive raw materials. Aker Industries explained that it also has expertise in manufacturing alumina, silicon-nitride, and mullite. It has been agreed that Ricardo will keep in contact with Aker Industries to monitor developments.

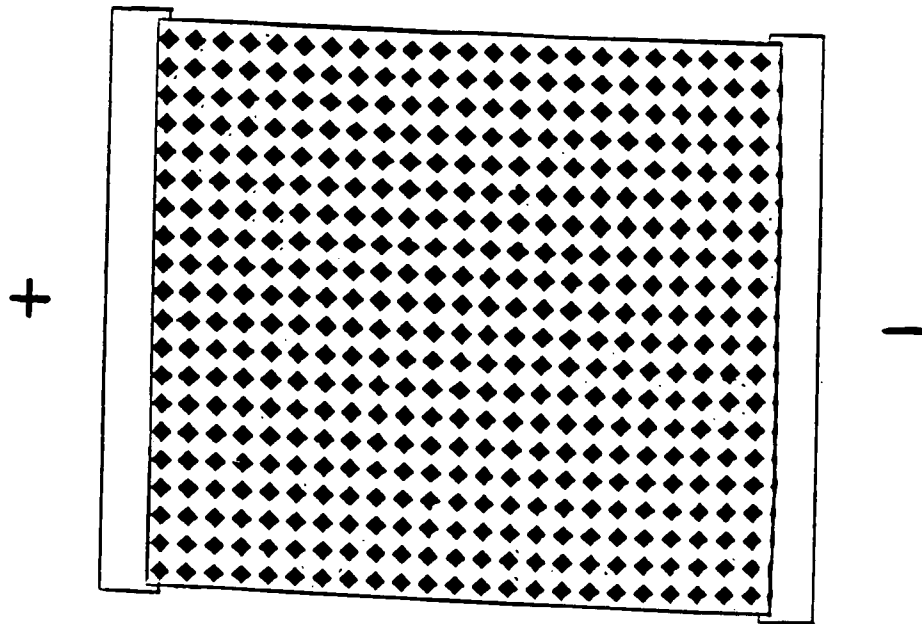
G. NGK

Representatives of NGK-Locke, Inc. met with EPA last February and discussed the possibility of working together on a cooperative trap development and evaluation program. NGK has considerable experience in developing wallflow cordierite honeycomb trap material but has never resistively heated conductive ceramics. Their cordierite traps have been evaluated in the EPA laboratory in the past with wire face-heaters. NGK is also capable of producing variable porosity traps to improve uniformity of soot loading and regeneration. NGK indicated at this meeting that they had some experience working with silicon-carbide and other conductive ceramics, but that they had not as yet produced a trap made of these materials.

EPA requested that NGK produce a wallflow-type trap made of silicon carbide or some other durable conductive ceramic. The configuration, which we believe lends itself to improved electrically heating, is a rectangular substrate design with a diagonal cell orientation relative to two electrical terminals. This trap configuration is shown in Figure 4. The idea is to allow uniform current along each cell wall between the terminals which are placed on opposite sides of the rectangular substrate.

Figure 4

Proposed NGK Wallflow Monolith
Si-C Resistive Trap Configuration



NGK has given no indication that they will attempt to investigate performing this development work in the near term.

H. Corning

Corning reported that it had invested \$2 million per year over the last 10 years on developing the wall flow monolith (WFM) for Diesel particulate filtration, but it was unlikely that this rate of investment would continue over the next two years.[14] Currently their sales of WFMs included Canadian Mines, who were successfully using WFMs in mining machinery and achieving particulate collection efficiencies of 90-95 percent. These machines run at a sufficiently high duty cycle such that auto regeneration of the filter takes place regularly and reliably. WFMs are still being supplied to engine manufacturers for particulate filtration development, and it was reported that many manufacturers were conducting tests with burner regeneration systems despite the high cost of burners and control systems and the reliability and safety question marks.

Corning reported that a typical burner used in these applications, a Webasto, cost around \$5,000 each. It was Corning's opinion that in a bypass system, two filters would be needed since raw exhaust would not want to be allowed to bypass straight to the atmosphere. It was mentioned that development work was still continuing with the Mercedes-Benz 300 TD filter.

Corning claimed that sufficient studies have been performed developing regeneration strategies such that durability problems with Corning WFM's have been overcome. It was reported that a 15-inch diameter by 15-inch long unit supplied by Corning has completed 4,000 hours of operation with no problems. Corning also added that they had had no vehicle recall claims on three-way catalyst substrates since 1975.

Corning was asked whether any of their current programs involved the development of electrically regenerable Diesel particulate filters (DPFs) using electrically conductive ceramic filter materials. Corning reported that they had worked with Sohio 10 years ago and had successfully extruded a silicon carbide WFM; however, sufficient porosity for DPF applications had not been achieved. There were also thermal shock resistance concerns with this type of DPF. It was reported that Corning had discussed the possible application of a silicon carbide WFM DPF with Ontario Research during the proposal stage of the current EPA/Ricardo contract. Corning also reported that they had made some new developments with electrically conductive materials which may be of interest for DPF applications, but would not discuss these until outstanding patent issues had been resolved, probably later this year.

III. Future Work

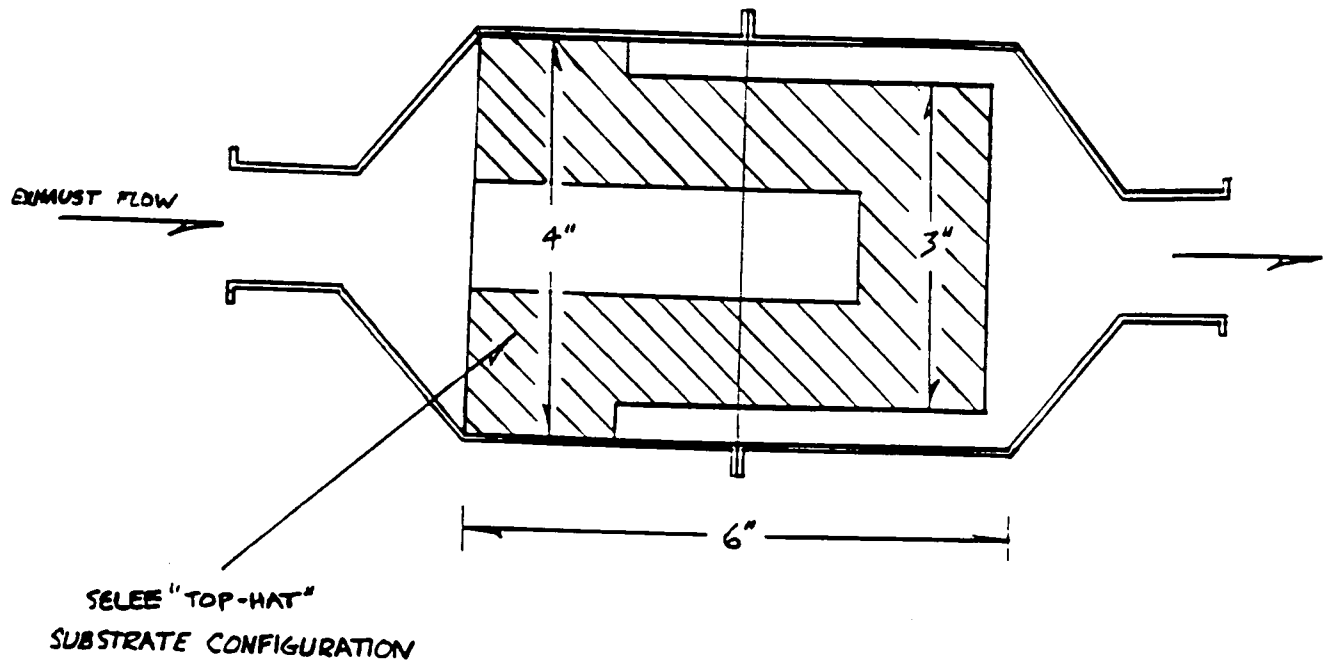
A. Selee

John Howitt (formerly of Corning) visited EPA in May 1988 and is fabricating samples of reticulated foam which he claims can be, but may not need to be, resistively heated.[15] Selee will soon be delivering samples of these foams for EPA evaluation. A picture of the trap configuration initially envisioned is shown in Figure 5. This trap configuration is in a "top-hat" shape such that all particulate must flow through an enhanced surface area axially and escape through the sides and outlet end both radially and axially.

Selee has since decided to change this configuration to the one shown in Figure 6 for ease in fabrication. EPA is currently fabricating the container shown in Figure 6 to be

Figure 5

Proposed Selee Diesel Trap
Evaluation Configuration



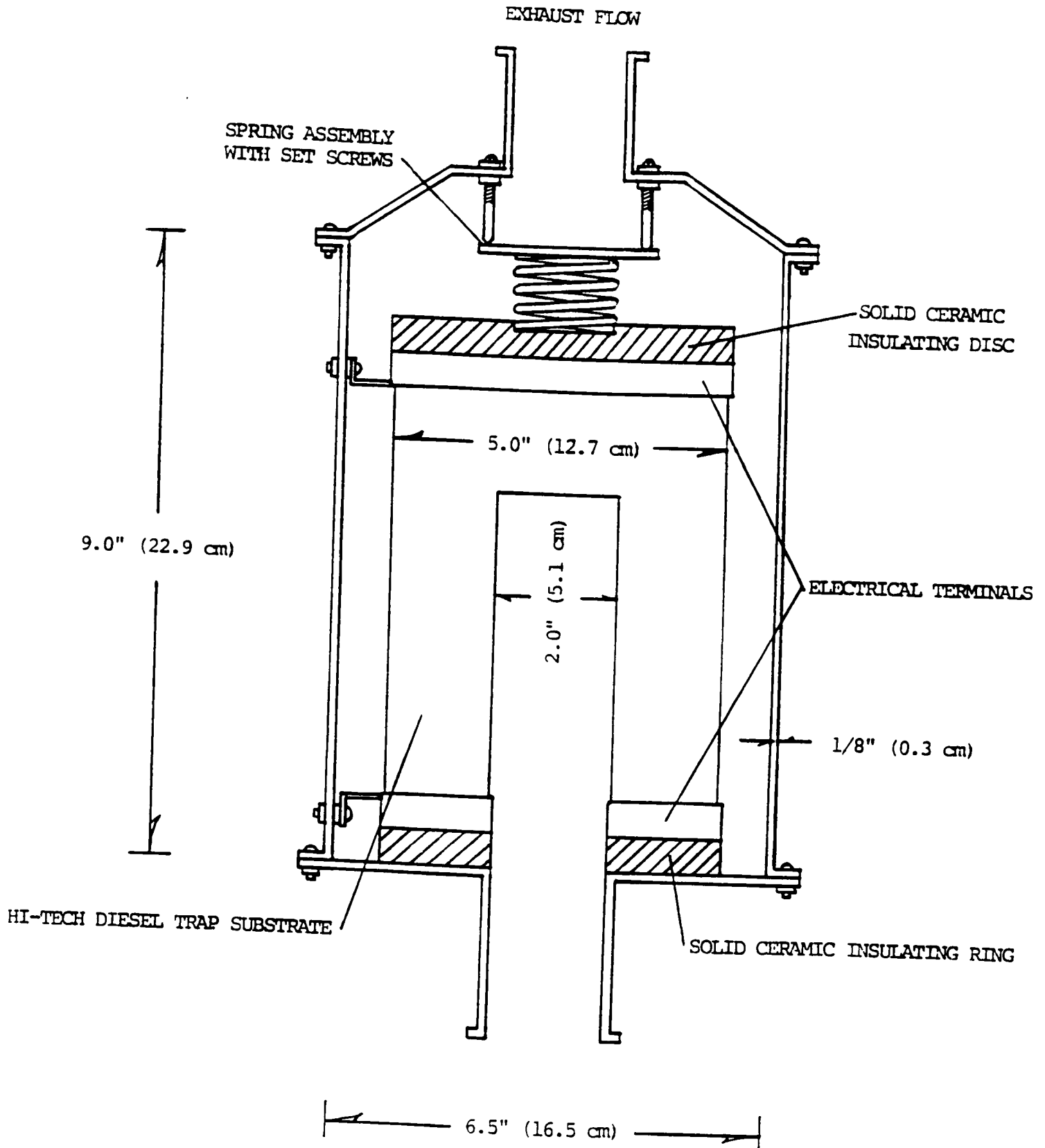
used for not only the Selee material, but for other material configurations as well. It is designed to be easily adaptable to other trap material configurations that EPA may be evaluating in the near future. The Selee material is currently being fabricated in their Switzerland plant and should be shipped to EPA for evaluation sometime this Fall. Selee is also attempting to produce materials which are proprietarily catalyst coated and made from silicon carbide and other conductive ceramics in case the initial samples do not show the filtering or regeneration characteristics Selee anticipates.

B. Hi-Tech Ceramics

As mentioned in the previous section, Hi-Tech Ceramics has provided some initial unoptimized samples, EPA has performed some preliminary evaluation of this material and it has been found to be resistively heatable. Ricardo also performed some filtering efficiency (backpressure buildup) tests on these samples and have determined that the loading characteristics of the material are inadequate. In fact, the particulate blows through the substrate rather than adhering to it and increasing

Figure 6

PROPOSED DIESEL TRAP EVALUATION CONTAINER



backpressure like a conventional trap. The reason for this is the low material density at 45 ppi. EPA advised Hi-Tech Ceramics to configure the next samples in 80 to 100 ppi for improved filtering. It is recognized, however, that the increase in density will also require an increase in external energy required to regenerate. Hi-Tech is currently retooling for these design changes and should also be providing the more optimized trap samples for EPA evaluation sometime later this Fall.

C. Equipment Status and Other Material Suppliers

The EPA laboratory is currently functional for all aspects of Diesel particulate control technology evaluation. Particulate sampling and analysis systems have been repaired and improved over the past year and test rigs have been and are being fabricated to handle a wide variety of test material configurations. The Mercedes 300D test vehicle has been kept in proper maintenance and all other instrumentation is set up and operational. Other material suppliers have been contacted and may also be providing samples for EPA evaluation. Among these companies are Brunswick Technetics, Camet, Nippon Ceramics, Union Carbide, Norton Industrial Ceramics, Cheltenham Induction Heating, and Mohawk Sintered Alloys, Inc.

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IV. References (cont'd)

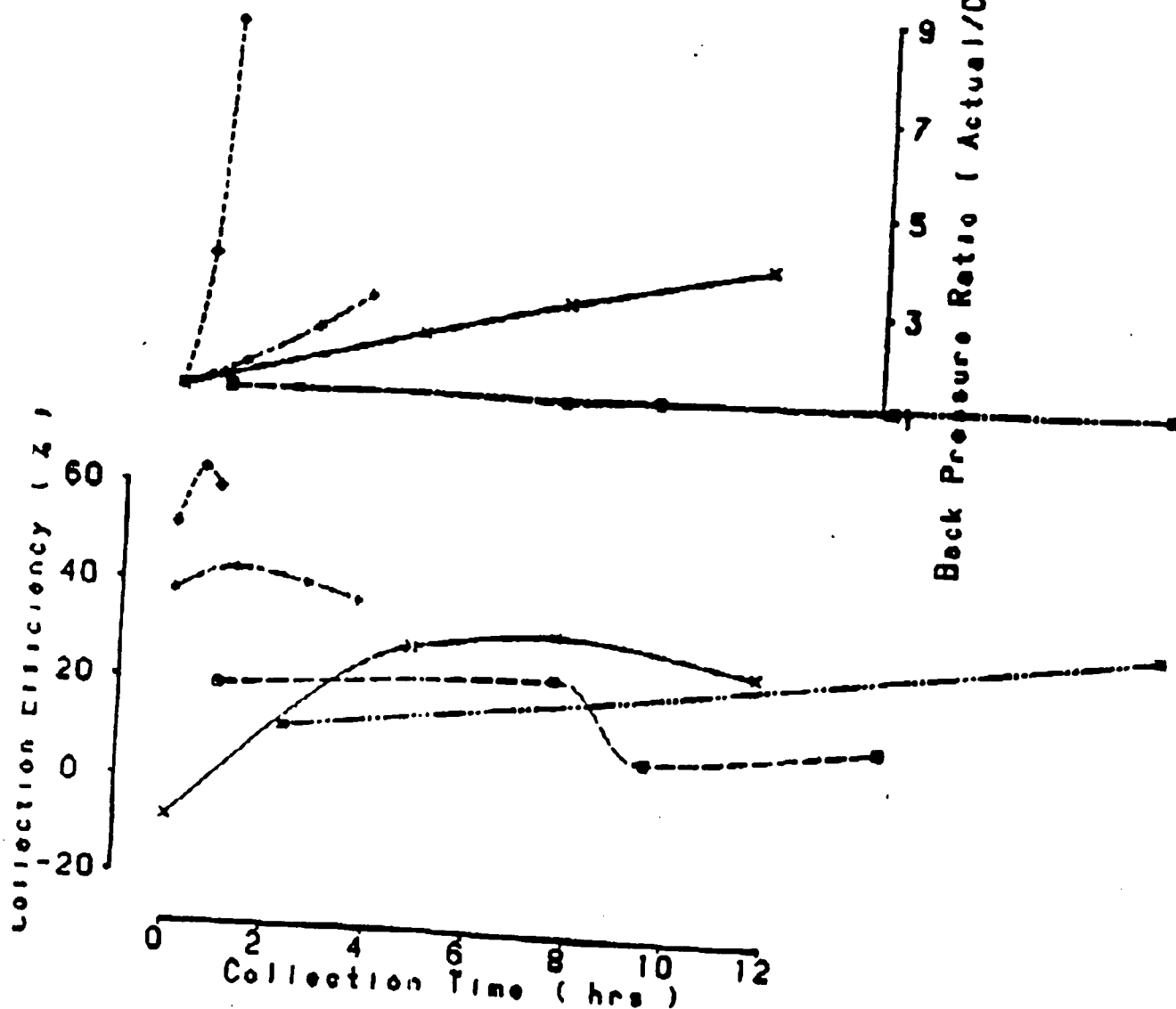
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V. Appendix

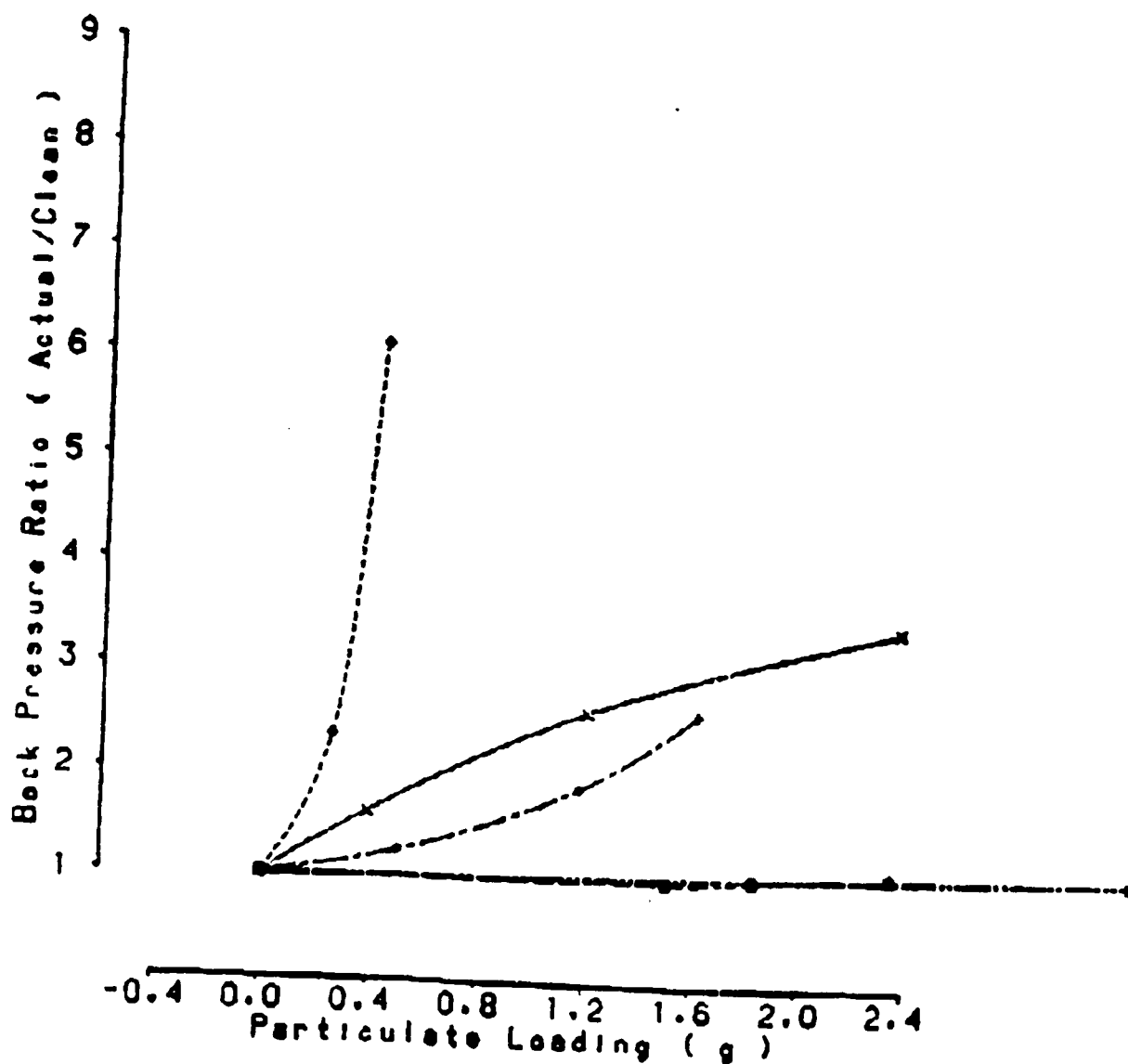
DPF Material Characterisation Tests
 VW 1.8l IDI - One Cylinder Tests
 X—X Standard Oil SIC Foam - 80 ppi - 25 mm Thick
 +—+ Coloroll Standard DPF Element
 □—□ Duriron Foam with Downstream Integral Membrane
 — Hi-Tech Foam
 — Hi-Tech Foam - Reduced Exhaust Gas Flow Rate
 Collection times Corrected to 100 cc³ Flow Area



DPF Material Characterisation Tests

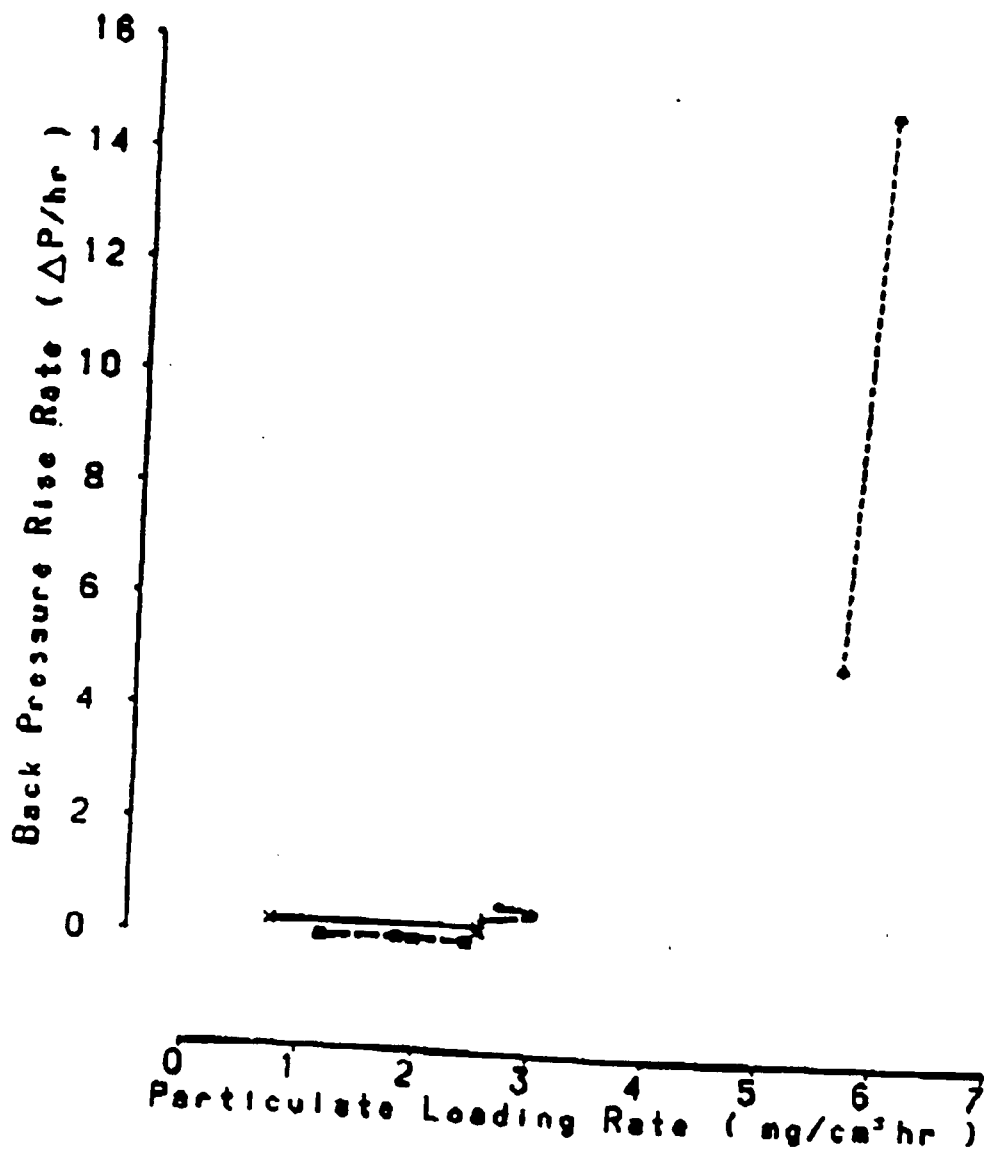
VW 1.6i 101 - One Cylinder Tests

- X—X Standard Oil SiC Foam - 80 ppi - 25 mm Thick
- ◇---◇ Coloroll Standard DPF Element
- +---+ Duriron Foam with Downstream Integral Membrane
- Hi-Tech Foam
- *---* Hi-Tech Foam - Reduced Exhaust Gas Flow Rate



DPF Material Characterisation Tests
 VW 1.8i IDI - One Cylinder Tests

- ×-----× Standard Oil-SiC Foam - 80 ppi - 25 mm Thick
- ◇-----◇ Coloroll Standard DPF Element
- +-----+ Duriron Foam with Downstream Integral Membrane
- Hi-Tech Foam
- *-----* Hi-Tech Foam - Reduced Exhaust Gas Flow Rate



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February 5, 1988

TO:

ATTN:

SUBJECT: Addendum No. 1 to SwRI Proposal 08-2857A-, "Development of a High-Temperature Resistant Diesel Particulate Trap"

L BACKGROUND

This addendum to the subject proposal was prepared as a result of encouraging experimental data and favorable responses from the consortium participants. The initial project resulted in the acquisition of significant generic data pertaining to the regeneration of trapped particulate. Using these data, several approaches to improve current regeneration techniques, and suggest new ones, were identified. One of the new approaches identified was to experiment with alternate trap media intended to withstand the highly exothermic combustion of trapped diesel particulate.

The alternate trap medium briefly experimented with was a silicon carbide foam. This foam was evaluated using a heavy-duty diesel engine in a transient test cell. Based on preliminary tests, trap efficiency was good and the resistance to regeneration excellent. Several areas require further development. These areas include trap design considerations, trap efficiency determinations, application of regeneration techniques, and long-term durability. This addendum outlines a proposed work effort to investigate the aforementioned areas.

Because of the successful approach of using multiclient sponsorship, this addendum proposes to continue the previous consortium format. New participants are able to join this work effort under the same conditions as new participants were able to join the original consortium. Improvements in the overall management and direction of the consortium will be implemented based on the suggestions received from the current participants.



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II. STATEMENT OF WORK

This section describes the objectives, approach, and scope of work proposed. The scope of work will remain flexible because of the exploratory research nature of the project.

A. Objective

The primary objective of this addendum will be to design and evaluate a high-temperature resistant diesel particulate trap. To meet this primary objective, several tasks are required, each with its own objective. During the first part of the past consortium, the objective was to obtain generic data to better understand regeneration. This addendum's activity will be more specific to hardware design and development of an actual system.

B. Approach

The approach to meet the primary objective will include some analytical work, but principally experimental efforts. Results and conclusions from the past consortium activity will be used to assist in the experimental test plan design. For example, the character of particulate produced from different engines will be important in the design and effectiveness of the particulate trap. By using the earlier consortium results, selection of engines and their operating cycles will be made to represent the different characters of particulate. The first material that will be used will be a silicon carbide foam. If the results using the silicon carbide do not warrant continued development, other alternate materials will be identified and evaluated.

C. Scope of Work

Southwest Research Institute Department of Emissions Research proposes to perform the following items of work to meet the principal objective. Because of the exploratory nature of this program, detailed test plans will be prepared as required for each area of need. Several plans of performance covering specific time periods will be prepared and submitted during the course of the project.

1. Task 1 - Trap Design, Engine Selection, and Baseline Tests

The initial design of the silicon carbide foam trap briefly evaluated in the past consortium's activity consisted of an assembly of silicon carbide "doughnuts." The number of "doughnuts" and the design of the trap container were selected arbitrarily. After additional engine evaluations, improvements in the trap container design will be made. The objectives of this phase of the project will be to evaluate several trap designs using the silicon carbide foam. These evaluations will be performed on a engine that emits low organic soluble particulate. The evaluations will be concerned primarily with trap efficiency, trap capacity, backpressure effects, and effects on engine operation and emissions. The effect of trap location in the exhaust, as well as engine transient cycle effects, also will be determined.

Several of the tests used to address the aforementioned trap parameters will be repeated on two additional engines. The first of these additional engines will

be an engine having particulate which is highly organic. This engine selection will assist in determining the effects of significant particulate character differences on trap effectiveness. The second engine will be one that has an advanced combustion chamber design, or perhaps a two-stroke engine.

This task will conclude with the successful design of a particulate trap medium and trap container that will exhibit acceptable efficiency and short-term durability on a variety of engines. These engines will be subjected to various operating conditions. Trap regenerations will be performed using a simple burner. Regeneration techniques to be used in association with the alternate trap medium will be examined under a separate task.

2. Task 2 - Trap Durability

After an acceptable trap design has been developed, the durability of the trap medium and container will be determined. Two simultaneous durability experiments are proposed. The first experiment will involve a stationary dynamometer and a cycle that will result in a high-temperature "aging" of the material. For example, engine speed and torque excursions to achieve high and low exhaust temperatures will be performed on an isolated trap to determine its long-term thermal resistance. The trap will be isolated from vibration to examine only the thermal aspect of trap integrity. Particulate emissions will be used to monitor trap efficiency, and will therefore serve as an indicator of trap deterioration. Other pertinent information such as temperature measurements, visual examinations, and x-ray examinations will be used as required.

The second durability experiment will involve the use of a full-size truck or bus. This experiment will be concerned primarily with the physical strength of the trap as it is exposed to vibrational forces during public road operation. The heavy-duty chassis dynamometer will be used to periodically determine the trap efficiency and any effects the trap may have on the engine. As in the aforementioned first durability experiment, pertinent parameters will be monitored while the vehicle is on the road and on the dynamometer.

As each durability experiment is being conducted, a controlled, burner-assisted regeneration will be used to clean the trap. These controlled regenerations will constitute a third durability experiment (i.e., resistance to multiple regenerations). Review of data from each durability experiment probably will result in suggestions to improve a particular aspect of the trap system. These improvements will be implemented until a satisfactory, durable trap has been achieved.

3. Task 3 - Trap Regeneration Techniques

This task will involve experimenting with regeneration techniques that could be applied to the trap system identified in Task 2. Depending on the composition of the trap medium, certain regeneration techniques are more appropriate than others. For example, use of electrical heat is much more attractive for silicon carbide than for silica due to their differing thermal properties (thermal diffusivity, thermal conductivity). The electrical heat can be applied either directly through the silicon carbide or indirectly via embedded heater elements.

The application of catalysts and the use of fuel additives will be investigated to examine their benefits in reducing the temperature requirement for regeneration. Adaptation of state-of-the-art burner systems will be performed only if the consortium participants request this approach. We feel that the sole development of a burner system would be redundant with on-going research by others, but we would research a particular aspect of an available burner system if its adaptation to our alternate trap system would be beneficial.

The effectiveness and durability of the regeneration technique will be investigated by designing an experimental test plan to perform repetitive regeneration cycles on a trap system. These experiments will be performed on an engine in a transient test cell. During this evaluation phase, improvements in the regeneration technique will be made until an acceptable approach to regenerate the trap has been identified. As part of the regeneration technique development, the controls and sensors required to initiate the regeneration will be identified. These sensors and controls include, where applicable, engine backpressure, various temperatures, bypass valve, etc.

4. Trap/Regeneration System Demonstration

After successful completion of Tasks 1 through 3, it is proposed that a high-visibility demonstration on a full size truck or bus be a part of this project. The complete trap/regeneration system will be installed on a selected vehicle and placed in service. The purpose of this task is to publically show the successful development of a particulate trap system as a result of cooperative research.

III. REPORTS AND REPORTING

Detailed progress reports will be forwarded to each participant in three copies at the end of each two months. A final engineering technical report in five copies will be prepared and submitted to each participant within 45 days after the experimental portion of the project is complete. This report will include discussion of the various design considerations as well as summarized data and findings. All reports and data obtained under this project are considered proprietary to the participants and will be disclosed only to the participants. The EPA will be kept abreast of the project, but will not be given any detailed data unless the participants instruct SwRI to do so.

It is planned that a one-day project seminar be held in April 1989, and another one near the end of the project at Southwest Research Institute. The dates of the seminars, to review progress and status of the project, will be finalized after the consortium has been formed. The Advisory Group plus up to two additional participants from each member company could attend these seminars, along with representatives from the EPA and ARB (Air Resources Board), if approved by the consortium members.

IV. TIME AND COST ESTIMATES

The minimum level of effort proposed for this project is \$450,000 on a cost reimbursement basis. The exploratory nature of the specific experiments and the required flexibility to redirect the technical effort, if necessary, make a cost reimbursement contract appropriate. In order to begin this program, ten

participants, each funding \$15,000 a year for two years, are required. Additional participants will result in an increase in the level of effort at project initiation. The cost estimate assumes that engines will be supplied at no charge by the participants to serve as particulate generators. All labor, fuels, traps, and any incidental expenses are included in the proposed level of effort. Attached is a copy of the contract addendum for your review and approval. It is essential that the contract be approved as is unless there is a substantial problem. In this way, all participants will have a common agreement with SwRI in the shortest possible time.

The project will require about 24 months to complete, exclusive of the final report. This estimate is based on obtaining the necessary engine and traps from the suppliers rapidly. The first 12 to 14 months are allocated to Task 1 - Trap Design, Engine Selection and Baseline Tests, and Task 2 - Trap Durability. The remainder of the project (10 to 12 months) will be devoted to Task 3 - Regeneration Techniques, and one month for Task 4 - Trap/Regeneration System Demonstration. Target date for project initiation is about June 1, 1988. The project can begin earlier, if approved before that date.

V. PROJECT MANAGEMENT

Article XII of the Consortium Agreement defines the Advisory Committee as one person from each participating organization and one person from SwRI. The defined purpose of this committee is to provide liaison, review, and recommendations related to the project.

One of the first requirements of the Advisory Committee will be to approve engine selections and assist in their supply to SwRI. If no agreement can be reached easily on engine selection, SwRI will make such decision and seek to acquire the engine.

Early in the project, a detailed draft plan of performance will be prepared and mailed to the Advisory Committee. The Advisory Committee will be asked to respond quickly with comments, suggestions and recommendations on the plan. SwRI will attempt to incorporate as much of the input from the Advisory Committee as possible within time and budget constraints, thereby finalizing the plan. It is anticipated that due to the wide scope of interests by the participants, not all ideas for research will be accommodated. In this case, modifications to the test plan will be at the discretion of SwRI. Final decisions on research will be the authority and responsibility of SwRI.

The Emissions Research Department of SwRI will be in charge of this project, and the project manager will be Bruce Bykowski. The project leader will be Robert Fanick. Others lending support to this project will be Charles Hare, Director of the Emissions Research Department, and Terry Ullman, Senior Research Engineer. Several other Institute staff members from other divisions will be used as consultants in the area of ceramics and electronic controls.

VI. SUMMARY

It has been a pleasure to prepare this addendum to the SwRI research activity pertaining to particulate traps. We have attempted to address the important points requested by our past consortium members in the preparation of the follow-on study.

The proposed activity will truly expand our knowledge in particulate trapping and regeneration by applying past results to the development of a full size trap/regeneration system. We are now confident that we are in a better position to develop a workable system that can benefit all the participants.

Quite frankly, the level of effort to achieve total success is unknown because the degree of required research is unknown. We do feel, however, that the effort proposed will contribute significantly to the development of a particulate trap system that incorporates the findings of our past consortium, and should result in a prototype device. The more participants joining, the better the chances for success. We encourage all past consortium participants to support our continued work, and will actively seek new support.

As mentioned earlier, the target date for starting the project is June 1, 1988, or earlier. In order for this date to be met, it is essential that we receive your response to this addendum and associated contract by May 1, 1988, or earlier. By offering this additional follow-on study as an "addendum" to a current project, we hope that your company's internal review process will be simplified. Those potential participants who were not members of the original consortium will be sent the original proposal and contract (08-2857) along with this addendum (08-2857A).

Please feel free to contact Mr. Bruce Bykowski regarding items of a technical nature, or Ms. Sharon Rowe for business and contract items. We look forward to your favorable review and early authorization.

Submitted by:

Approved by:



Bruce B. Bykowski
Manager, Advanced Technology
Department of Emissions Research



Charles T. Hare
Director
Department of Emissions Research

cc: Robert Fanick