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Diesel Particulates Destruction by Electrical Discharge Technique

Final Report

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FOREWORD

This work was sponsored by the State of California Air Resources Board (ARB) under Standard Agreement No. A0-047-32 dated August 27, 1980. The period of performance was from September 22, 1980 to March 31, 1981. The Project Manager at the ARB was Mr. J. Paskind. This work was partially supported by JPL discretionary funds and by the JPL transportation program sponsored by the U.S. Department of Energy. Partial results were presented in a seminar, arranged by the Motor Vehicle Association and sponsored by the Air Resources Board, in Detroit, Michigan, October 14, 1980. This work was performed by the personnel in the JPL Control and Energy Conversion Division, Chemical and Biological Processes Section.

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

EXECUTIVE SUMMARY

This report summarizes the results of a research and development effort on a new technique which can destroy the particulates produced by a diesel engine powered vehicle. Close-spaced, comb-shaped electrodes are charged alternately by high voltage of opposite polarities. When the engine exhaust carrying the particulates flows through the electrodes, the particulates trigger spark discharges in the latter, which in turn destroy the particulate. A prototype hardware study has demonstrated the following:

(1) The technique is very effective in destroying the particulates if they have agglomerated into large size particles, several micrometers or larger in diameter. Destruction efficiency as high as 70% has been observed. This figure could be further improved if the hardware design is optimized.

(2) The major product of the destruction process is the carbon dioxide. The amount of other gaseous products such as carbon monoxide, hydrocarbons, NO_x and ozone produced by the process is small. The rates of these emissions by a full-scale particulates destruction device are estimated to be 20 to 100 times smaller than those specified by the U.S. Environmental Protection Agency for the light duty vehicles.

(3) The electrical power required to operate such a destruction device is small and is affordable by light duty vehicles. For a moderate particulate emission or destruction rate, the electrical power required can be made to be 50 watts or less. This high power efficiency is attributed to the release of energy by the particulates through their own fast combustion.

(4) A key problem has been identified; that is, how to dynamically agglomerate the particulates. Several ideas, such as self-release filters and a fluidized bed particulates agglomerator, have been explored and further effort is required in order to perfect a device for the agglomeration of the particulates.

GLOSSARY OF TERMS AND SYMBOLS

BACK PRESSURE	Pressure in the exhaust pipe measured at an upstream point close to the grid device
DIESEL PARTICULATES	Solid carbonaceous particulates emitted in the exhaust of a diesel engine. Typical size: 0.01 to 0.1 μm
AGGLOMERATED DIESEL PARTICULATES	Several or many individual diesel particulates which physically stuck together to form a large particle. Typical Size: 1 to 10 μm
DESTRUCTION EFFICIENCY	Ratio of mass of diesel particulates destroyed by the grid to that prior to the test
DISCHARGE CIRCUITS	Electronic hardware which provides a high voltage bias to the grid or storage of high voltage energy for spark discharge in the grid, plus possible control components
ELECTRICAL DISCHARGE (or SPARK)	High current arc or plasma in air formed between high voltage biased grid electrodes and initiated by electrical breakdown
ELECTROSTATIC PRECIPITATOR (ESP)	A device which separates fine particles or aerosols from ambient gas by first charging them and subsequently separating them by an electrical field
ENERGY/MASS RATIO	Electrical energy required to destroy unit weight of diesel particulates (in kJ/g)
EQUIVALENT ELECTRICAL POWER	The minimum electrical energy required for destruction of diesel particulates produced by one second of operation of a diesel engine. (Typical engine under typical operation conditions)
FLUIDIZED BED	A system in which gas is flowing in a particle bed enabling particles to freely move around
GFA FILTER	A glass fiber filter Grade A, similarly GFC is for Grade C
GRID	A set of comb-shaped plate electrodes which can be biased with alternate polarity and assembled in an electrical insulated frame
HC	Hydrocarbons
NO_x	Nitrogen-oxygen compounds, e.g., NO, NO_2
TGA	Thermal Gravimetric Analysis, an instrument which measures weight loss of materials as a function of time or temperature
PULSE ENERGY (SPARK ENERGY)	Total electrical energy contained in an electrical discharge formed spark

a	radius of a particle or a particulate
c	specific heat
C	electrical capacitance (in μF)
d	diameter of a particle or particulate
D	spacing between a pair of adjacent grid electrodes
e	spark energy, or pulse energy
E'	activation energy
E_o	average electrical field strength between the grid electrodes
E_{max}	maximum electrical field around a small dielectric particle placed in the electrical field between grid electrodes
E_1	breakdown electrical field strength of air
h	heat of combustion of particulates (kJ/g)
I	discharge current
J	current density
L	electrical inductance
$\dot{m}$	mass generation rate of diesel particulates
$\dot{N}$	total number of spark (electrical discharge) per unit time
$\dot{n}$	number of particulates per unit time
P	electrical power
P_{min}	minimum average electrical power required for the spark discharges to destroy particulates from a diesel engine. Not included is the power required by the electronics.
P_{com}	power supplied by the total combustion of diesel particulates at a rate equivalent they are generated by the engine
R_o	universal gas constant (1.987 cal/mol/K)
R	arc resistance of the spark
$\dot{r}$	reaction rate
T	temperature
Δt	duration of the spark discharge
t_c	characteristic time of reaction (oxidation) of particulates

$\dot{V}$	exhaust volume flow rate of a diesel engine
V_o	volume of a single spark
v_f	characteristic velocity for fluidization in a fluidized bed
α	ionization fraction in plasma
ε	dielectric constant
η	viscosity of air (in centipoise)
κ	thermal diffusivity
μm	micrometer = 10^{-4} cm
ρ	density of diesel particulates
ρ_b	density of fluidized bed particulates
ρ_g	density of gas in the fluidized bed
σ	mass per area of diesel particulates collected on a filter paper
τ	thermal time constant
w	weight
$\frac{dw}{dt}$	weight loss rate
$\frac{dE}{dm}$	energy/mass ratio

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. OBJECTIVES

Conduct critical experiments using preliminary prototype hardware to demonstrate

(1) that a significant quantity of diesel particulates can be destroyed by electrical discharge, and

(2) that real time measurements of particulate mass flow might be estimated using the electrical discharge technique.

The purpose of the work was not to develop an optimized solution to the problem, but to provide a basis for defining a program to quantify the effectiveness of this technique, develop and test prototype hardware and assess the feasibility of its application to a diesel engine.

II. INTRODUCTION - DIESEL PARTICULATES PROBLEM

Particulate emission may be a limiting factor for the wide acceptance of diesel engines for vehicle propulsion. Due to its efficiency, the diesel engine has been considered an immediate solution for alleviating the gasoline fuel shortage. Recently, the diesel gaseous pollutant emissions have been reduced to an acceptable level (Reference 1), however, the particulate emission, which is about two orders-of-magnitude more severe than the emission of a gasoline engine of the same power, still has no adequate solution.

It is generally believed that particulates of small sizes (submicrometer) such as those emitted by a diesel engine, are potentially potent as a health hazard to the human respiratory system, especially when they have adsorbed polycyclic aromatic hydrocarbons. The regulation established by the U.S. Environmental Protecton Agency (Reference 2) set average particulate emission rates of 0.6 g/mile and 0.2 g/mile as the mandatory limits which will be permitted for a diesel powered passenger car for 1981 and 1983 respectively. Current domestically produced diesel passenger cars have typical particulate emission rates of 0.6 - 0.8 g/mile. Thus, a reduction of the particulate emission level of the order of 30 to 75 percent is necessary. Similar regulations are also imposed on light-duty trucks.

The automotive industry is expending considerable effort to alleviate this problem. Three front-runner approaches being considered are: (1) modification of engine design, especially the fuel injection system, to reduce the particulates formation (Reference 3), (2) adding chemicals to the fuel to suppress the particulates formation, and (3) filtering the particulates and subsequently destroying them by heat. So far none of the approaches appears to be successful. Approach (1) is difficult because the combustion process in a diesel engine is not well understood and there is a limit as to how far the electronically controlled fuel injection system can achieve particulate suppression. Approach (2) is not highly desirable because the additives may generate additional pollutants and induce depositions in the engine. Approach (3) is under the most extensive development and testing. Over 10 different types of particulate filters or traps have been evaluated, but so far none of them has been proven to be totally satisfactory. The best collection efficiency of the order of 60 to 70 percent may not be sufficient for reducing the particulate emisson to an acceptable level. Almost all filters introduce a back pressure in the diesel engine exhaust system, and this back pressure increases rapidly with time due to particulate accumulation. Therefore a frequent regeneration of the filter is necessary. A commonly used technique is by throttling the air inlet, i.e., changing the fuel/air ratio. Under this condition, the temperature of the exhaust can reach over 600°C (1100°F) so that oxidation of trapped particulates by the residual oxygen in the exhaust can be achieved. This is a time consuming process, and many minutes of operation are usually necessary. Frequent regeneration will result in the decrease of engine overall efficiency and possibly durability. The durability of filters themselves is also questionable due to the specified 50,000 mile low particulate emission requirement imposed by the EPA regulation. Decrease of particulate collection efficiency after many high temperature regeneration cycles has been reported, and the sulfate particulates appear to be a severe problem associated with the filtering technique. The front-runner filter is the porous cordierite ($2MgO$-$2Al_2O_3$-$5SiO_2$) honeycomb structure originally developed for gasoline engine exhaust catalyst support. The alternate cell channels are blocked to form the filter. It has been tested up to 2,000 miles equivalent operation time with 10 to 20 regeneration cycles. Optimization of filter parameters has been studied (Reference 4).

III. BACKGROUND - ELECTRICAL DISCHARGE PARTICULATES DESTRUCTION TECHNIQUE

In this work, we have studied the use of a pulsed electrical discharge technique to eliminate the particulates. The exhaust gas from a diesel engine is allowed to pass-by a high voltage biased grid. Small amounts of electrical energy are stored in a capacitor of the bias circuit. The particulates in the exhaust stream, being electrically semiconductive, are capable of initiating spark discharges across the grid-gas interface. The spark in the gas has a high temperature (>5000°K) and high plasma density. Thus, it can erode and/or induce combustion of the particulates. It is believed that elimination of a significant part of the particulates can be achieved. In addition, this technique offers a potential solution to another practical diesel particulate problem; namely that there does not exist today a system to measure dynamically the particulate mass in diesel exhaust streams. Instrumentation of spark currents appears to provide a measurement of particulate flow.

The approach is a spin-off from a carbon/graphite fiber detection system (References 5 and 6). The effort was sponsored by the NASA Langley Research Center in order to develop an instrument system that could detect fine conductive carbon fiber fragments released from a fire of a carbon fiber composite which is to be used for fabrication of aircraft components. The released fiber has a diameter of 6 to 8 μm and a typical length ranging from 1 to 5 mm.

Open grids with straight electrode spacing ranging from 1 to 5 mm were mounted in front of a small windbox to sample the fiber fragments which were suspended in the air. The grid electrodes were biased in alternate polarity so that sparks could be initiated between any two adjacent electrodes upon bridging by a fiber. The bias voltage, which was a function of the sampling rate and the grid spacing, ranged from 500 to 1200 V. The capacitance of the high voltage energy bank was typically 0.05 to 0.15 μF. Under optimized conditions, one fiber fragment could generate a single spark discharge for accurate counting. A unique feature was that the electrical field attracts and aligns the fiber with the grid so as to achieve a high counting efficiency. It was observed that the spark could partially damage and consume the fiber. Fiber fragments with lengths smaller than the grid spacings could generate spark counts if the bias voltage was sufficiently high. These characteristics indicate that the approach could be extended to the counting and destruction of diesel particulates.

Of course, the size of the diesel particulates (typically 0.01 to 1.0 μm) is much smaller than a carbon fiber. This makes it easier for the particulates to be destroyed by spark discharge. For the typical spark discharge duration of 0.1 to 0.5 μs, the estimated inward thermal penetration depth from the particulate surface is larger than the radii of the particulates. Therefore thorough heat transfer from the spark to the particulates can be assured for the destruction processes. In order to achieve the spark generation efficiency, the small particulate size requires that the grid spacing be much less than 1 mm. Preliminary tests have shown that diesel exhaust particulates could not generate sparks in a 1 mm spacing grid system biased with the highest applicable high voltage. However, when the spacing was reduced to less than 250 μm, high voltage sparks were generated both directly from the diesel engine exhaust, and by passing collected agglomerated fine diesel particulates through the grid as they were carried by an airstream. Thus, the basic feasibility of diesel particulates initiated sparks was demonstrated. The destruction process and the destruction efficiency remained to be studied and demonstrated in this project.

IV. PHYSICAL FOUNDATION OF THE TECHNIQUE

Limited tests and analyses were performed to answer the following questions: first, why diesel particulates can initiate electrical sparks in a high voltage charged grid, and second, why a high voltage spark can destroy a diesel particulate.

1. Electrical Conductivity of Diesel Particulates

Diesel particulates are an amorphous type of carbonaceous material. Usually they are considered electrically nonconductive. It was suspected that the particulates might have some low level of electrical conductivity as indicated by the fact that they have the capability of initiating sparks in a high voltage charged grid.

A pellet of collected diesel particulates, 4.6 mm (0.180 inch) in diameter and 5.1 mm (0.200 inch) in height was press-formed under a consolidation pressure of 4.08×10^3 N/m^2 (60 kpsi). It weighed 0.123 g; therefore, it had a density of 1.47 g/cm^3. A resistance of 600 Ω was measured across the two ends to give a specific resistivity of 154 Ω-cm. This test verified that considerable electrical conductivity exists in diesel particulates.

2. Physics of Spark Initiation

The initiation process depends upon the relative size of the particles and the grid spacing. It is discussed in the following cases (Fig. 1).

(a) Large Particles - Directly shorting the grid electrodes

The case has been well studied in previous carbon fiber detection work (References 5 and 6). Upon contact of the particle with a pair of high voltage biased adjacent grid electrodes, arcing will occur at the points of contact. Initially, an electrical current will flow through the particle. Due to the relatively low electrical conductivity of the particulates compared to the arc conductivity of the air plasma, the arc will grow so as to completely bridge the electrodes. A high current is then established through the arc in the air instead of in the particle, and the plasma of the arc will surround the particle.

(b) Large Particles - Not shorting the grid electrodes

The grid usually is biased at a voltage much below its self-spark voltage. The effect of introducing a large conductive particle

- LARGE PARTICLE

  – FIELD ENHANCEMENT

$$E \simeq \frac{V}{d_1 + d_2} > \frac{V}{d_0}$$

- SINGLE SMALL PARTICLE

  – LOCAL FIELD ENHANCEMENT

$$E_{max} = \frac{3\epsilon}{\epsilon + 2} E_0 \quad \text{DIELECTRIC}$$

$$= 3 E_0 \quad \text{CONDUCTOR}$$

- MULTIPLE SMALL PARTICLES

$$E_{breakdown} = f(n)$$

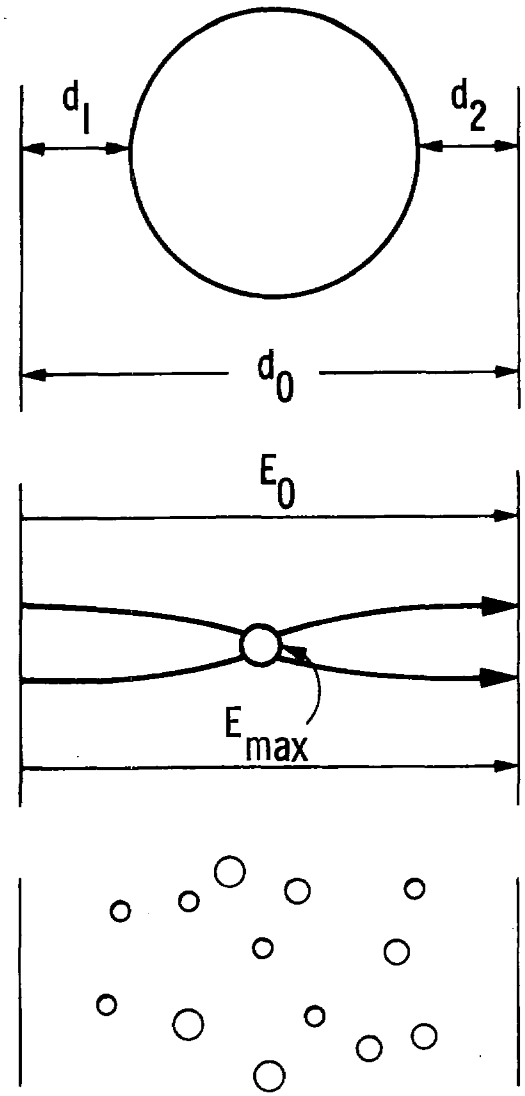


Fig. 1. Schematic Representation of Spark Initiation Criterion

between the grid electrodes is to increase the effective field strength between the particles and the electrodes. For instance, if the plate grid has a spacing D and is biased by a voltage V, the field strength in the grid is $E_0 = V/D$ originally. If a large particle of diameter d is introduced between the pair of adjacent grid electrodes, the field strength will increase to approximately $E_1 \approx V/(D-d)$. Thus, spontaneous discharge (arcing) can occur between the particle and the electrodes if the E_1 exceeds the breakdown voltage of the air.

(c) Single Small Particles

In this case, the perturbation on the electrical field E_0 between grid electrodes is small. The maximum electrical field around the particle, by using elementary electrostatic calculation, is as follows:

$$
\begin{aligned}
E_{max} &= \frac{3\varepsilon}{\varepsilon + 2} E_0 && \text{for dielectric particles} \\
&= 3E_0 && \text{for conductive particles}
\end{aligned}
$$

where ε is the dielectric constant of the particle. One can see that an electrical field enhancement effect is achieved and an electrical breakdown can be initiated if the bias voltage is sufficiently high. Caution is needed however, in applying this concept to a very small particle because the breakdown phenomenon may be size-dependent, so that, if the size is too small, a breakdown will not occur even though the E_{max} according to the above equations may well exceed the usual breakdown field strength of the air.

(d) Multiple Small Particles

The situation is complicated because there are electrostatic interactions between the particles under the electrical field. It is suspected that the breakdown field (arcing voltage) is a decreasing function of the particle density.

3. Thermal Gravimetric Analysis (TGA) of Diesel Particulates

Fig. 2 shows the TGA test results of a typical collected diesel particulates powder. It was tested by using 2 mg of the particulates and a heating rate of 30°C/min. Below 100°C, no weight loss was observed. Between 100°C to 500°C, gradual weight loss was observed both in air and nitrogen ambient gases. Thus, it is suspected that part of the weight loss was due to the volatile composition in the particulates. Between 500°C to 600°C rapid weight loss was observed in air but not in nitrogen, indicating the former to be an oxidation process. The 600°C temperature is usually reported as required for regeneration of diesel particulates traps (Reference 4). There was an apparent 4 percent residual in the sample due to the presence of iron oxide in the sample.

4. Reaction Rate as a Function of Temperature

By reduction of the TGA data between 500°C to 600°C, shown in Fig. 2, the following equation for rate of reaction (oxidation) $\dot{r}$ is obtained:

$$\dot{r} = 6.21 \times 10^6 \times \exp(-E'/R_0 T) = -\frac{1}{w}\frac{dw}{dt}$$

where w = weight of the particulates sample

and E' = 34,054 cal/mol

R_0 = universal gas constant

= 1.987 cal/mol/°K

Note that the value of the activation energy E' is quite agreeable with typical values of activation energy for carbonaceous material such as the coals and carbon fibers.

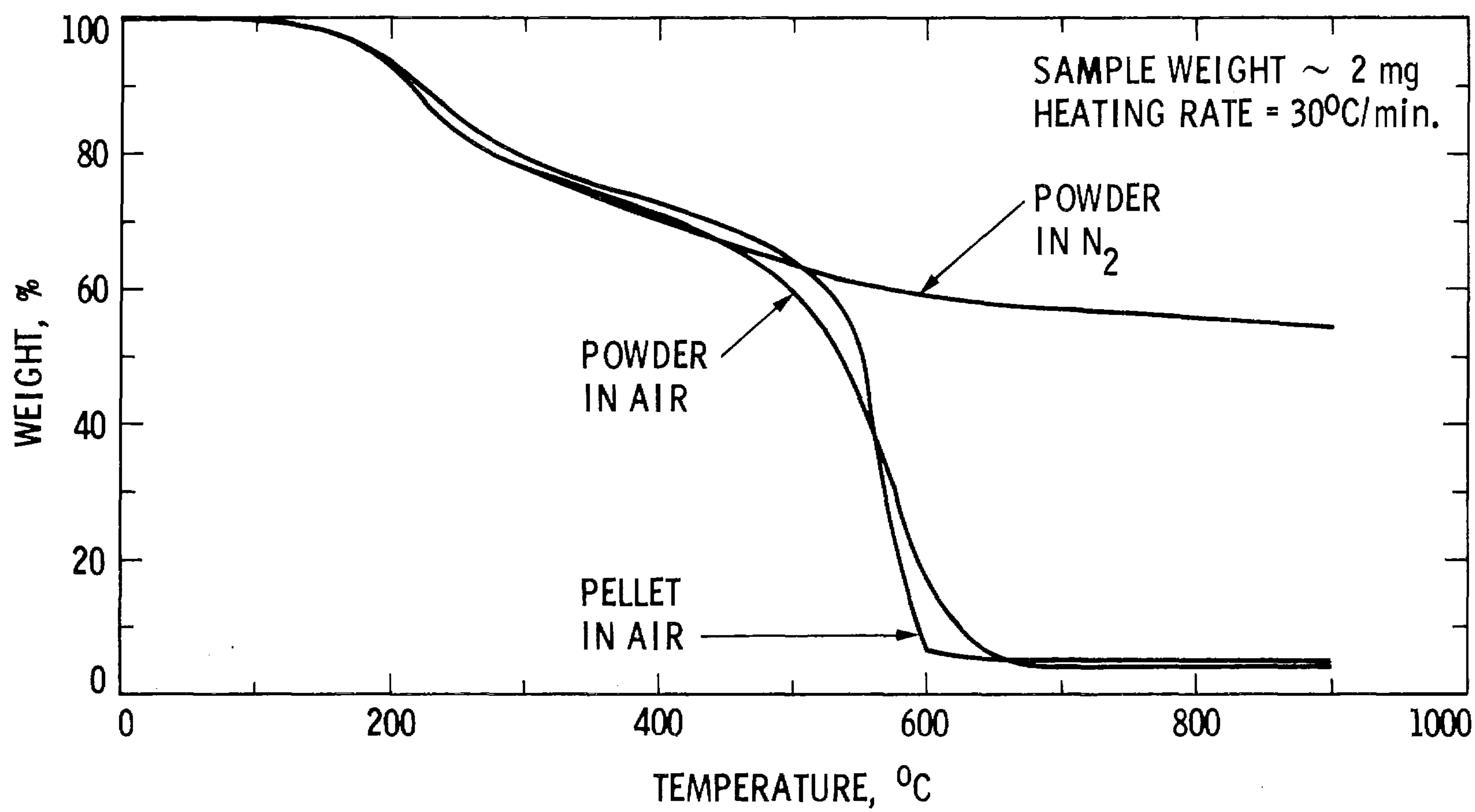


Fig. 2. Thermal Gravimetrical Analysis of a Typical Diesel Particulate Sample

An attempt was made to extrapolate this rate equation to assess the reaction (oxidation) rate at higher temperatures. The results are as follows:

T,°K	1000	3000	5000
$\dot{r}$, s^{-1}	0.224	2.05×10^4	2.02×10^5
t_c, s	4.5	4.9×10^{-5}	5×10^{-6}

where $t_c = \dot{r}^{-1}$ is a characteristic time as required to complete the reaction under the constant given temperature. The results indicate that at a high temperature of 5000°K, the reaction can be completed in microseconds, -- a time comparable to the typical duration of a spark discharge in the high voltage charged grid. While this extrapolation is yet to be verified, we did have some evidence in later tests showing that the microsecond- duration electrical discharge in the grid does induce completed combustion of the diesel particulates.

5. Air Spark Plasma Characteristics

Our next question is "can the electrical discharge produce a high temperature as required for fast particulates oxidation?"

The high voltage discharge formed spark is an unconfined, high density plasma formed in the air. It is not a well studied physical phenomenon. Our studies have indicated that it is a self-regulated plasma of relatively constant temperature, that is, its volume increases with the energy (voltage or capacitance in the discharge circuit). Thus, its energy density and temperature are of relatively constant values insensitive to the energy parameters . Based upon some tests in the carbon fiber work in which sparks formed between millimeters spacing grids with bias voltages of 500 to 2000 V, the following typical physical properties are estimated:

Peak Discharge Current I	$\sim$100 - 200 A
Volume of spark V_o	$\sim$1 - 3 mm^3
Current Density J	$\sim$5,000 - 10,000 A/cm^2
Energy Density dE/dV	$\sim$7 J/cm^3
Temperature T	$\sim$4,000 - 7,000°K
Ionization Fraction α	$\sim 10^{-3}$
Electrical Resistance R	$\sim$0.5 - 2.0 Ω
Duration Δt	$\sim$0.5 - 2.0 μs

6. Heat Transfer

Examining the heat transfer process from the plasma generated by the spark discharge to the particulates is another way to understand the effectiveness of the oxidation process. The characteristic time constant τ of heating up a spherical particle of radius a by a constant high temperature ambient is:

$$\tau = \frac{a^2}{\kappa}$$

where κ = diffusivity of the particle.

$\simeq 10^{-3}\ cm^2/s$ for carbonaceous materials

Thus, for a = 0.1 μm, $\tau \simeq 10^{-7}$ s and for a = 1.0 μm, $\tau \simeq 10^{-5}$s, i.e., for submicron size particulates, sufficient heat penetration could occur in the particulates to initiate combustion (oxidation). For larger particulates, which consist of a number of small particulates, because of the obvious porosity in them, and the low particulate electrical conductivity, the plasma of the discharge may occur inside to support effective heating.

The other two possible mechanisms which are favorable for supporting the plasma induced combustion (oxidation) of the particulates are: (1) the presence of free oxygen radicals in the plasma, and (2) the plasma etching, i.e., vaporization of the particles by the bombardment of high energy ions in the plasma.

7. Summary

From the above discussion, it is not surprising to discover that a short-duration high energy density spark discharge can destroy diesel particulates through the high temperature spark induced combustion of the particles, if sufficient oxygen is present around the particulates.

V. ENGINEERING FOUNDATION OF THE TECHNIQUE

The most important engineering consideration of using electrical discharge for diesel particulates destruction is the energy or power efficiency. In practical applications, there is an upper limit in energy or power that can be reasonably supplied by a light-duty vehicle.

To perform an order-of-magnitude estimation of the power requirement for an efficient electrical discharge diesel particulates destruction device, the following reasonable assumptions are used:

Energy per spark e:	10 mJ
Volume of single spark V_0:	1 mm^3
Particulates emission mass rate $\dot{m}$:	1 g/mile
	$\simeq 8.3 \times 10^{-3}$ g/s
	(assuming 30 miles/hr)
Average particulate diameter d:	0.5×10^{-4} cm
Density of particulates ρ:	1.0 g/cm^3

Thus

$$\text{Particulate number rate } \dot{n} = \dot{m}\,(1/6\,\pi d^3 \rho)^{-1}$$
$$\simeq 1.3 \times 10^{11}\ s^{-1}$$

The rate of exhaust volume $\dot{V} \simeq 5 \times 10^4\ cm^3/s$.

One can see that in the 1 mm^3 spark volume, there are 2.6×10^3 particulates. In order to destroy all the particulates, the entire exhaust has to be treated by the spark. The number of sparks per unit time $\dot{N}$ required for this process is

$$\dot{N} = \dot{V}/1\ mm^3 = 5 \times 10^7\ s^{-1}$$

The total power P required is

$$P = \dot{N} \times 10^{-2}\ J = 5 \times 10^5\ W.$$

This power level is far beyond that which can be supplied by an ordinary vehicle, i.e., in order to increase the power efficiency the number of particulates being destroyed by one spark has to be increased two to three orders of magnitude. In practice, this means the particulates have to be agglomerated before they induce the spark discharge.

The following is an estimate of the minimum power P_{min} that will be required for total destruction of diesel particulates emitted by a diesel light-duty vehicle:

$$P_{min} = \dot{m}\, c\Delta T$$

where

$$c = \text{specific heat of particulates}$$
$$\simeq 1.3 \text{ J/g.}$$
$$\Delta T \simeq 5000°K$$

It has been assumed that when the particulates reach a temperature of 5000°K, they will be completely oxidized. Thus

$$P_{min} \simeq 54 \text{ W}$$

and

$$c\Delta T \simeq 6.5 \text{ kJ/g}$$

The heat of combustion (oxidation) h of typical carbonaceous material is about 30 kJ/g. Thus the combustion power P_{com} of diesel particulates is:

$$P_{com} = \dot{m}\, h$$
$$\simeq 250 \text{ W}$$

In other words, if the combustion of diesel particulates is successfully initiated, the total power required can be made much smaller than the estimated 54 W. It will be the amount of power needed to initiate the particulates destruction, and no additional power is necessary to sustain the combustion process.

VI. HARDWARE AND EQUIPMENT USED IN THE STUDY

1. Grids

Parallel plate type grids were used for the electrical discharge diesel particulates destruction tests. This type of construction has been previously developed in the carbon fiber detection work (References 5 and 6). It allows an in-depth electrical field path in the grid for the particulates and therefore provides greater probability of successful spark discharge initiation. For the diesel particulates destruction, the dimensions of the particulates are much smaller than typical carbon fiber fragments. Small, sub-millimeter grid spacings typically 500μm down to 125μm, are required.

In order to maintain an accurate spacing between the plate electrodes, a hard sheet metal was needed to fabricate the electrodes. Hard steel single edge razor blades were found to be suitable. The blades were 3.8 cm (1.5 inch) long along the razor edge and 1.78 cm (0.70 inch) wide in the direction perpendicular to the razor edge. After removal of the blade edge protection strips from one side of the blade, it is essentially a flat plate of 0.25 mm (0.010 inch) thickness. One corner of the blades was partially ground off, and this corner was arranged alternately during the assembly (Fig. 3). As is shown in the figure, the blade electrodes were separated by two mylar spacers of an appropriate thickness. The spacers had a central hole for the purpose of inserting an insulator alignment pin. Usually, the blades were assembled in a Micarta frame. Indium metal was used to maintain a pressure contact for the electrical connection between the blades and two brass rod electrodes for high voltage biasing of the blades. For flow-type testing of diesel particulate destruction, the blades were sealed in a hollow Micarta frame (Fig. 4). For contact-type destruction of collected particulates, one side of the grid was fabricated to be slightly exposed to allow the contact of the particulates, e.g., collected on a filter (Fig. 5). The grid apertures were typically 3.8 cm (1.5 inch) x 1.27 cm (0.5 inch). Thus, for a 150μm spacing grid, approximately 32 blades and spacers set were used.

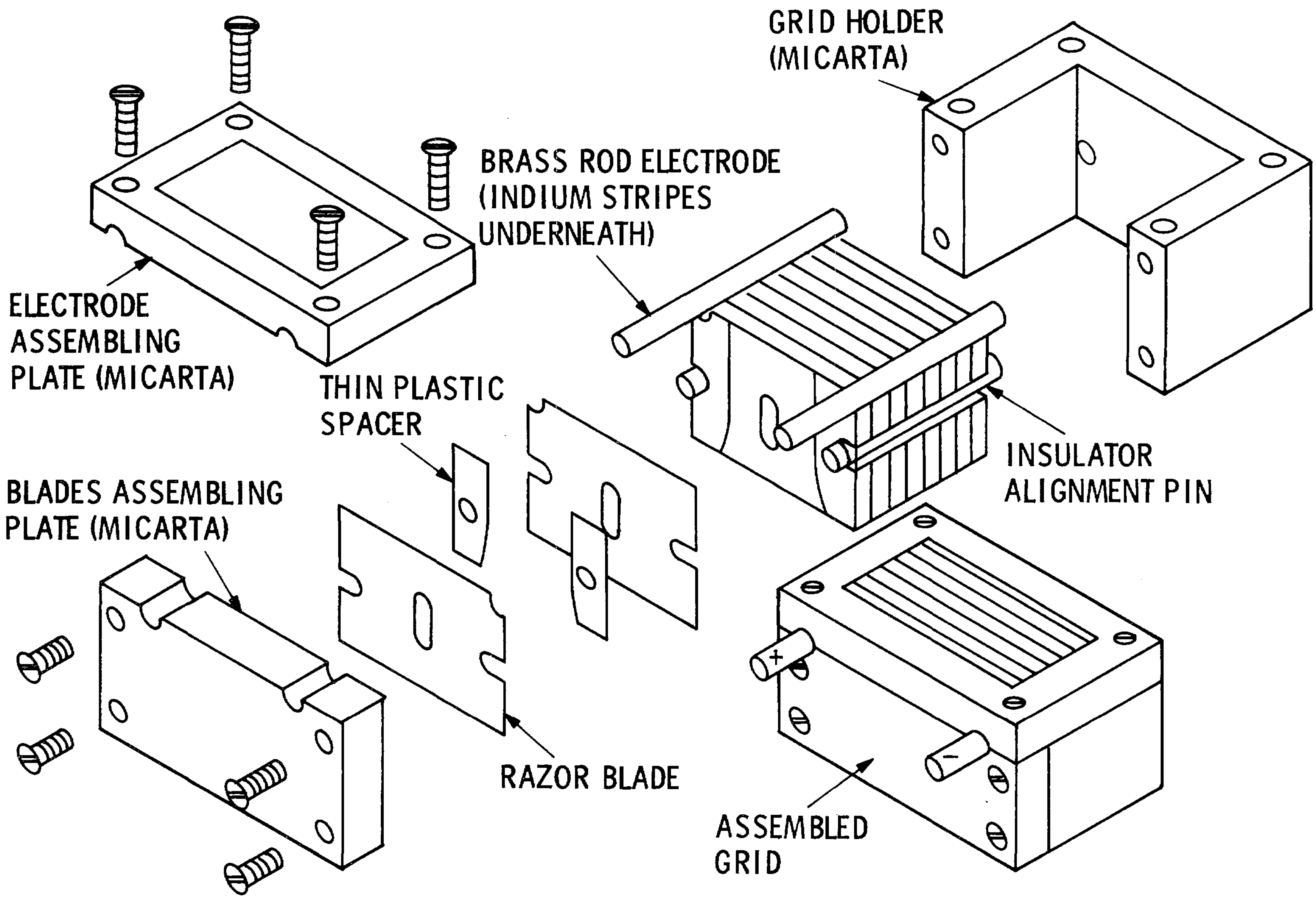


Fig. 3. Razor-blade Hollow Grid Construction

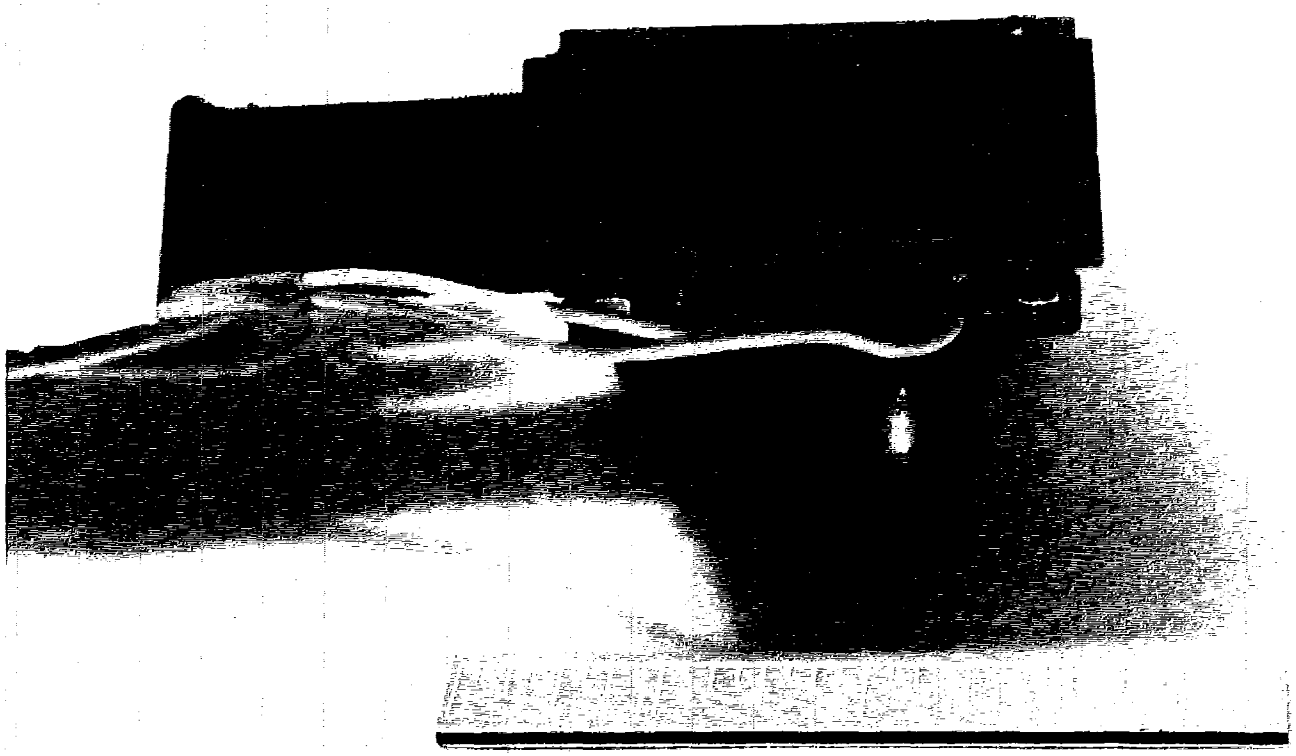


Fig. 4. A Small Spacing Flow-type Razor-blade Grid

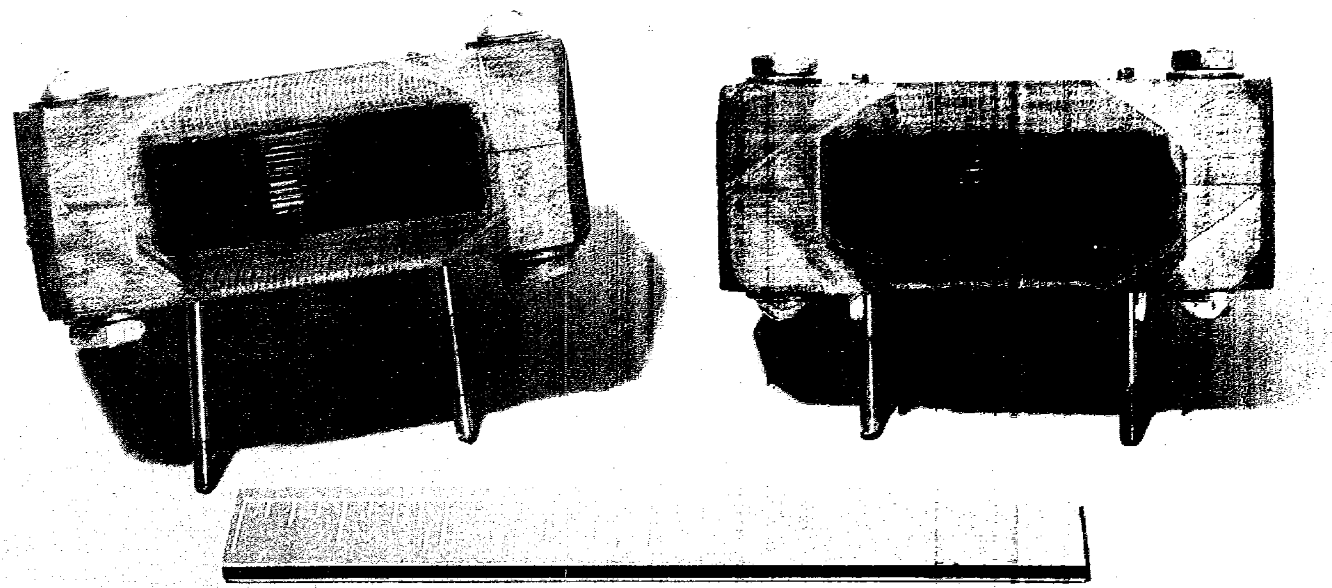


Fig. 5. Exposed Contact-type Razor-blade Grids

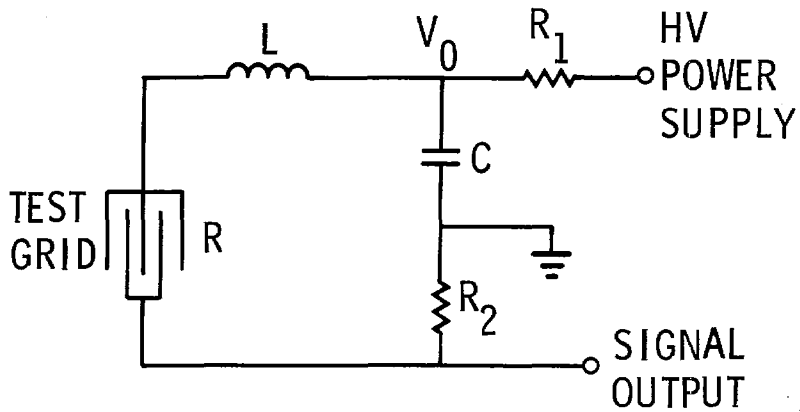
Two other types of grids were also used in the study. One larger grid was a scale-up of the razor blade grid. It was fabricated by 7.5 x 10.2 x 0.062 cm (3 x 4 x 0.025 inch) brass plates and 0.25 mm (0.010 inch) thick Teflon spacers and was assembled in a Micarta frame. The grid aperture was 7.5 x 1.27 cm (3 x 0.5 inch). The other type of grid was an one millimeter spacing grid used for previous carbon fiber detection work. It was fabricated by 0.51-mm thick copper strips. The grid aperture was 3.8 x 3.8 cm (1.5 x 1.5 inch) and the grid depth was 0.95 cm (0.375 inch).

2. Discharge Circuits

Two types of high voltage discharge circuits were used in the study. They are essentially the same types that were developed for the carbon fiber detection (References 5 and 6). The first type provides continuous bias on the grid for real-time particulate destruction by electrical discharge (Fig. 6). It used a 300 Ω current limiting resistor and a discharge capacitor of typical capacitance of 0.047 μF. A series current shunt was used to monitor the discharge current pulse to be counted by a portable digital counter. The second type circuit is a high voltage pulser circuit. It can provide periodic high voltage bias (discharge) to the grid at an adjustable rate up to 400 Hz and variable voltage range up to 2000 V. The discharge capacitor also had a capacitance of 0.047 μF (Fig. 7). The circuit was used for the static test of destruction of particulates collected on a filter paper. These circuits are suitable for relatively low rate discharge tests only. For a high rate operation, high power rating components would have to be used.

3. Particulates Sources

Collected agglomerated particulates were obtained from the General Motors Research Laboratory. The particulates used in most powder tests were in



R_1 = CURRENT LIMITING RESISTOR

$\simeq 300\,\Omega$

R_2 = CURRENT SHUNT

$\simeq 0.1\,\Omega$

$C \simeq 0.05\ \mu F$

L = CIRCUIT INDUCTANCE

$\simeq 0.5\ \mu H$

R = SPARK RESISTANCE

$\simeq 0.5\text{-}1.0\,\Omega$

$R^2 > \frac{4L}{C}$ EXPONENTIAL

$R^2 = \frac{4L}{C}$ CRITICAL DAMPED

$R^2 < \frac{4L}{C}$ OSCILLATORY

NOTE: R IS VOLTAGE DEPENDENT

Fig. 6. Schematic Diagram of a Continuous Pulse Discharge Circuit

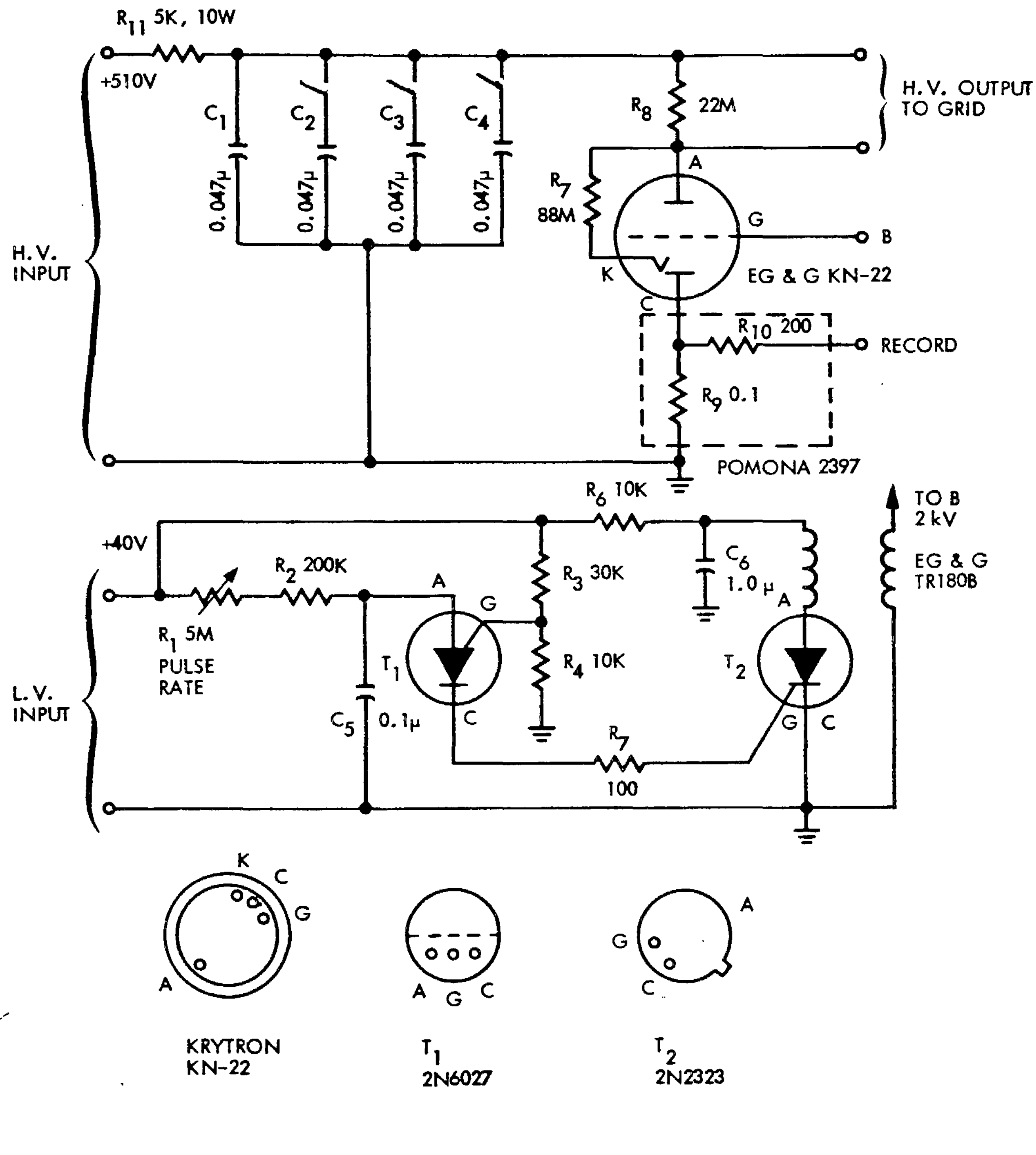


Fig. 7. Schematic Diagram of a High Voltage Pulser Circuit

fine granule form (150 - 200 μm). A Volkswagen 1500 cc Rabbit diesel engine donated by the VW of America, Inc. was used for the live testing. It was adapted with a water brake dynamometer for load control and RPM monitoring.

VII. LABORATORY TESTS

The purpose of the laboratory tests was to demonstrate the feasibility of destruction of collected agglomerated diesel particulates by electrical discharge and to determine the energy efficiency of such a destruction process. The tests were also performed in order to determine the end products of the destruction process.

1. Static Test - Destruction of Particulates Collected on Filter Papers

In this test, diesel particulates were collected from the exhaust of the VW Rabbit engine onto a 7-cm-diameter GFA glass fiber filter. The filter sample was then installed on a sealed fixture (buffered by another filter of the same type) under vacuum suction. An exposed fine spacing grid, described previously, was then placed on the particulate coated section of the filter. The high voltage pulse circuit described previously was used to generate the discharge (Fig. 8).

The discharge proceeded according to a preset rate selected for the discharge circuit and was terminated automatically, when nearly all the particulates on filter paper exposed to the grid were destroyed and the gaseous products exited through the filter into the vacuum cleaner chamber which was used to generate the suction flow. The amount of residual particulates which could not generate further discharge was negligible (Fig. 9). The use of the vacuum was a precautionary measure in order to prevent possible loss of particulates which may be sputtered and break free from the filter by the agitation of the sparks.

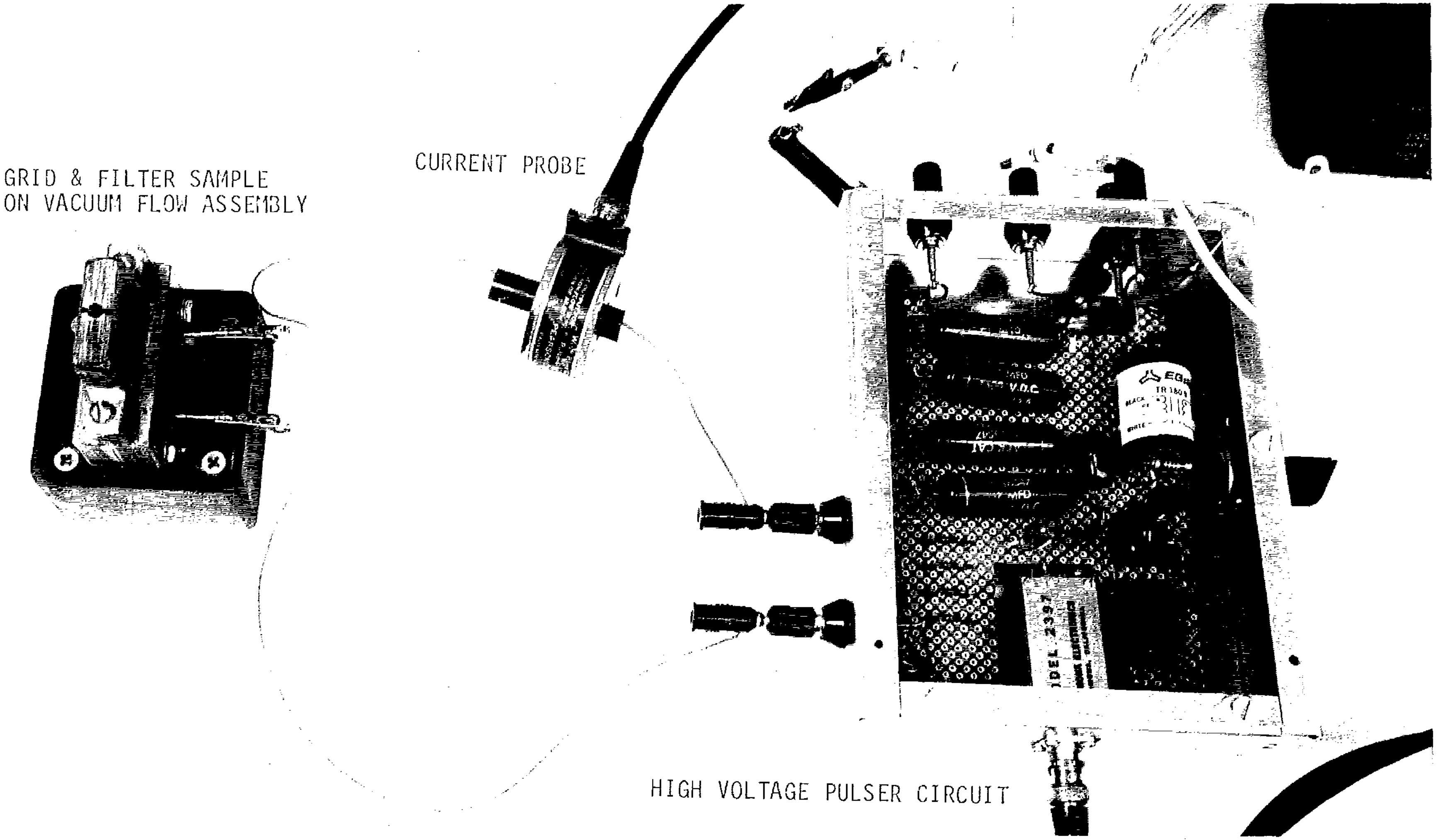


Fig. 8. Static Particulates Destruction Test - Particulates Collected on a Filter

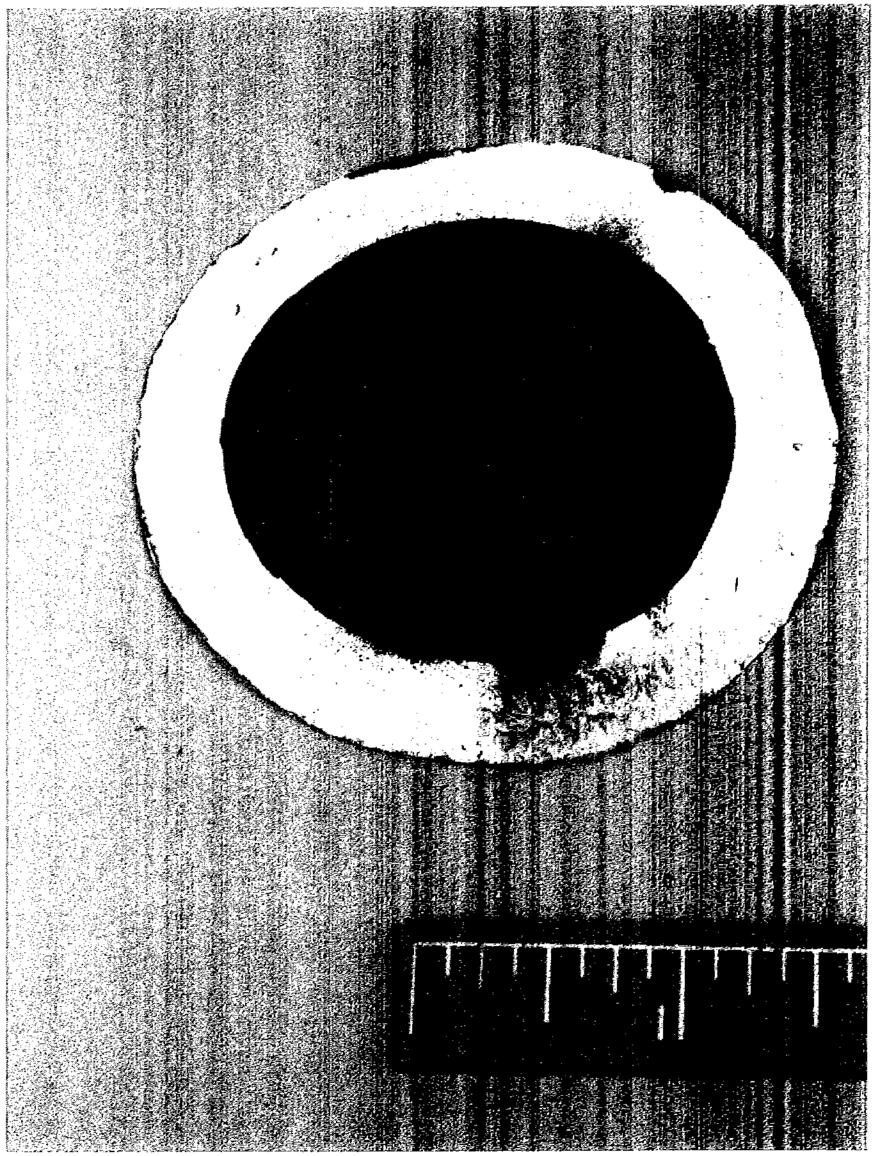


Fig. 9. Particulates Sample After Static Destruction Test

The adequacy of the glass fiber filter to stop ultra-fine (d <0.1 μm) particulates was studied. Although in the new filters, some large pores (∿0.5 μm) do exist, when they were exposed to a fair amount of diesel smoke, these pores were filled with particulates so as to become a very fine pore filter. No particulates were observed either in the second (back-up) filter or deep in the sub-surface of the first filter. An additional effort was made to precoat the second filter with a thick layer of fine (average size 0.05 μm) alumina powder. In this case, again, no particulates were detected in the filter. Thus, we feel reasonably confident that no significant amount of fine particulates escaped through the filter.

Two grids of grid spacing 0.25 mm and 0.51 mm were used for the test. Bias voltages of 510 V and 690 V were used to operate them, respectively. The results are shown in Table 1. The mass/area ratio σ of the particulates was determined by weighing the filter prior to and after the collection of particulates. The pulse energy was determined by the arc resistance of the spark and the peak pulse current as measured by a Pearson pulse current probe. The pulses had a half sine waveform and a duration of about 0.5 μs. Thus, the pulse energy can be calculated. The energy/mass ratio dE/dm was obtained by dividing the total energy (total number of discharges as recorded by the digital counter x the pulse energy) by the total mass destroyed (σ x area of the grid aperture). As described previously, the equivalent power was obtained by assuming 1 g/mile particulates emission rate or 8.3×10^{-3} g/s. It can be seen that most of the electrical power appears to be reasonably low for automobiles.

Table 1. Filter Experiment Test Results

MASS/AREA σ (mg/cm^2)	PULSE ENERGY e (mJ)	ENERGY/MASS dE/dm (kJ/g)	EQUIVALENT POWER FOR 1 g/MILE RATE P (W)
0.049	2.9	10.1	84
	7.6	16.2	135
0.084	2.9	3.6	30
	7.6	34.0	283
0.173	2.9	3.7	31
	7.6	19.2	160
0.227	2.9	6.3	52
	7.6	10.2	85
0.296	2.9	6.8	57
	7.6	15.4	128
0.547	2.9	14.8	123
	7.6	24.0	200

The above experiment was modified as follows in order to improve the power efficiency of the particulates destruction. It was determined that the thin particulates layer lying on the filter did not fully cover the sparks which had a hemispheric shape. In order to more efficiently utilize the energy of the spark, a thicker layer of particulates would be needed. A millimeter spacing grid (3.8 x 3.8 cm) described previously, was sealed on top of a clean GFA filter in the vacuum flow assembly. Collected particulates of a preweighed amount were filled into the grid and discharges commenced (Fig. 10). The average test results of 20 tests are summarized in Table 2. It can be seen that that the electrical power consumption is very low. The only possible interpretation of such low energy for particulates destruction is

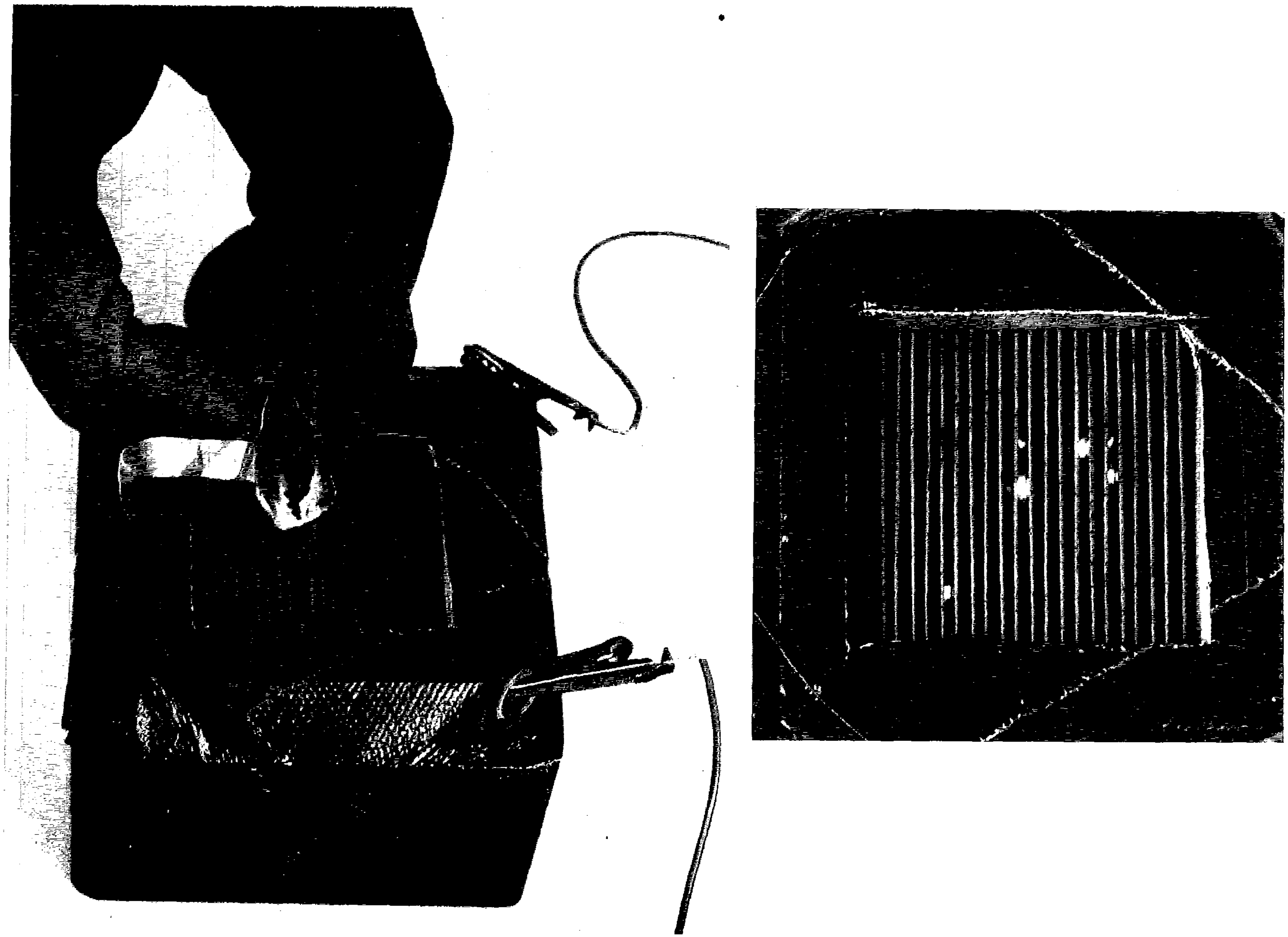


Fig. 10. Static Particulates Destruction Test - Particulates in Powder Form

that self-supported combustion of particulates of microseconds in duration was initiated by the electrical discharge.

Table 2. Static Diesel Powder Destruction Test Results

POWDER MASS M (mg)	NUMBER OF SPARKS N	ENERGY/MASS dE/dm (kJ/g)	EQUIVALENT POWER FOR 1 g/MILE RATE P (W)
10	220	0.405	3.4
20	490	0.445	3.7

Note: Grid biased at 1000 V. Spark energy = 18.2 mJ.

2. Simulated Dynamic Test - Destruction of Flowing Agglomerated Particulates

A clean GFC glass fiber filter was assembled in the vacuum flow assembly. A razor blade type fine spacing (150 μm) grid described previously, (Fig. 4) was hermetically sealed on top of it. In the top part of the grid frame was a fine mesh screen (#100 mesh) basket. A preweighed amount of collected, agglomerated diesel particulates was placed in the basket to be released into the grid gradually by stirring with a thin stick. The particulates were carried by the air flow into the continuously high voltage biased grid for spark destruction. By weighing the filter prior to and after the test, the amount of undestroyed particulates and the percentage of destruction were determined. Typical results are shown in Table 3.

The results show that reasonable destruction efficiency of the order of 30-60 percent was achieved. The efficiency depends on many parameters. For the small grid used, a higher flow rate (as controlled by the variac to operate

Table 3. Typical Test Results - Simulated Dynamic Particulates Destruction Tests

Variac Setting Vrms	Grid Voltage V	Capacitance μF	Sample Weight mg	Spark Counts	Destruction Efficiency
60	510	0.14	10	30,825	0.50
"	"	"	"	23,852	0.50
"	690	"	"	76,468	0.55
"	"	"	"	49,905	0.52
"	"	"	"	23,044	0.28
"	510/450	"	"	12,315	0.65*
30	"	"	"	17,132	0.60*
60	"	"	20	26,181	0.70*
30	"	"	"	26,181	0.74*
60	510	0.047	10	45,138	0.50
"	"	"	"	14,454	0.60
80	"	"	"	41,194	0.12
"	"	"	"	29,464	0.20
15	450	"	"	20,325	0.60
40	"	"	"	21,175	0.38
"	"	"	"	24,605	0.45
"	"	"	"	18,250	0.54
20	"	"	"	19,583	0.33
"	"	"	"	9,618	0.33
"	"	"	"	4,600	0.60
40	"	"	"	13,120	0.43
15	510	"	"	8,743	0.41
40	"	"	"	17,329	0.32
20	"	"	"	9,024	0.54
"	510/450	"	"	8,692/ 4,875	0.54*
40	"	"	"	12,194/ 6,665	0.62*
"	"	"	"	13,304/ 6,973	0.58*
15	"	"	"	5,182/ 2,946	0.62*
40	450	"	"	56,209	0.31
30	"	"	"	55,125	0.35
"	"	"	"	28,132	0.48
"	"	"	"	18,213	0.61
60	"	2.0	"	4,410	0.22
20	"	"	"	5,171	0.20
40	"	0.01	"	48,766	0.28
30	570	0.02	12	6,001	0.58
"	"	"	"	6,578	0.52

* 2 grids in series.

the vacuum cleaner) reduced the efficiency. The flow rate in the grid at a 30 Vrsm variac setting was about 1 m/s. High efficiency was observed for small capacitance down to 0.02 μF. A higher voltage or capacitance did not always produce a higher destruction efficiency. A limited number of tests were performed with two identical grids assembled in series. In these cases, a higher destruction efficiency of ∿70 percent was observed. The total number of spark counts was not always consistent because it depended upon the manner of manual agitation and the rate of release of the particulates powder. A TGA test of post-test collected undestructed powder on the filter has shown that the characteristics of weight loss as a function of temperature of the powder was essentially the same as the original untested powder as shown in Fig. 2. Thus, we believe that the reason particulates remained undestructed was due to the fact that no discharges were initiated by them, and not because of their partial weight loss as indicated by the TGA data at low temperatures (Fig. 2) nor their partial consumption (i.e., reduced particle sizes). Microscopic examination of individual particulates requires an electron microscope with high resolution (0.005μm) which was not available for our study.

3. Gaseous Products Test

This test was performed at the Haagen-Smit Laboratory of the California Air Resources Board in El Monte, California. The test procedures were the same as those for the simulated dynamic test described in Section VII-2 (a high current 450 V power supply was used to bias the grid). The vacuum cleaner was replaced by that of the sampling system of a gas analysis equipment that was available there.

The entire gaseous output of the particulates destruction test was sampled in a plastic sample bag at a rate of 250 ft^3/hr for a period of 50 seconds, i.e., total 98.32 liters of gas was collected in the bag. Three tests were performed. The results are summarized in Table 4. The amount of CO, NO_x and HC produced by the electrical discharge destruction of diesel particulates was insignificant. The amount is much smaller than the emission standards specified for light duty vehicles in Reference 2. A considerable amount of CO_2 was produced as one would expect due to the oxidation of the carbon. The theoretical mass of CO_2 is the amount of CO_2 which would be produced if the particulates consisted of pure carbon and they are completely combusted to form CO_2. These calculated values are about twice as large as those we have

Table 4. Gaseous Product Test Results

Test Number		1	2	3
Particulates destroyed, mg		12.5	49	23
Total spark counts		112,700	117,800	144,500
Background	CO_2, ppm	690	782	690
	CO	4	2.4	0.8
	HC	5.5	2.4	1.9
	NO_x	0.5	0.4	0.1
Net Produced by the destruction of particulates	CO_2, ppm	138	368	276
	CO	11	12.6	15.0
	HC	2.1	3.8	5.1
	NO_x	0.9	1.4	1.5
Mass of CO_2 measured, mg		24.8	66.2	49.7
Mass of CO_2 theoretical, mg		45.8	179.7	84.3

observed by the measurements. This may indicate that the particulates contain compositions other than carbon, for instance, hydrogen compounds. In fact, about 50 percent of weight loss in the TGA data shown in Fig. 2 prior to 500°C may not be due to the oxidation of carbon, as discussed previously.

One serious concern about the electrical discharge destruction technique has been the ozone production. It is well known that ozone is usually produced in an electrical discharge environment. A crude test was also performed at the ARB test facility. The gaseous output of the particulates destruction test was sampled into an ozone detection system at a rate of 2.2 liters/min. An approximate 3 ppm ozone was detected at a particulates destruction rate of about 4 mg per minute. Thus, about 3.3 μg of ozone is produced by electrical discharge destruction of 1 mg of particulates - a tolerable rate compared to the ozone generation rate by light duty vehicles. It is generally believed that about 10 to 30% of NO_2 produced by the engine is converted into ozone via photochemical reactions in atmosphere (Reference 8).

4. Remarks Regarding the Laboratory Tests

Test results have proven that good particulate destruction efficiency can be obtained by the electrical discharge technique. The power requirement of such a practical device also appeared to be reasonable. These are encouraging indications because the test hardware is not considered optimized. Our only concern is that the tests were performed in ambient air, not in an oxygen reduced environment presented in the diesel exhaust. However, we do not feel this is a very important question because sufficient residual oxygen generally is present in the exhaust (>2%). In case it is insufficient, extra air could be injected into the exhaust. The higher temperature of the exhaust will enhance the particulates destruction rate over that in the low temperature ambient air.

VIII. LIVE TESTS ON ENGINE

1. Test Without Pre-Agglomeration

Both close spacing ($\sim$150 μm) razor type grids and the brass plate grid (spacing $\sim$250 μm) were directly adapted to the end of the exhaust pipe of the VW Rabbit engine. High current rate, high voltage power supplies were used to bias the grids in order to assure a high discharge rate capability of the grids. Typically, at low RPM and low load, about 200 sparks per second were observed. When these test parameters were increased, the maximum discharge rate observed was about 800 sparks per second. We suspect that these discharges were initiated by the large particulates produced by the engine (which of course are low in number because the overwhelming majority of particulates are submicron in size). It is also possible that minor agglomeration of particulates could occur on the interior walls of the exhaust system and produce particulates of a larger size. Thus, we can conclude that without pre-agglomeration of the particulates, it is difficult to implement the electrical discharge destruction mechanism. Also, as indicated in the previous discussion, it would be impossible both energy and power wise to implement such a system for destruction of all separated particulates.

2. Survey of Pre-Agglomeraton Techniques

The most feasible techniques for agglomerating fine particulates produced by the diesel engines are: (1) the electrostatic precipitator (ESP), and (2) the integrated grid-filter assembly. Both concepts are illustrated in Figures 11 and 12 in a self-explanatory manner. ESP can be made very efficient if the design parameters are optimized. The main technical difficulties are related to the relatively high flow rate in a diesel exhaust, the high moisture content (therefore a leakage current problem) and the miniaturization. In principle, if the ESP has a sufficiently large flow cross-section, i.e., a

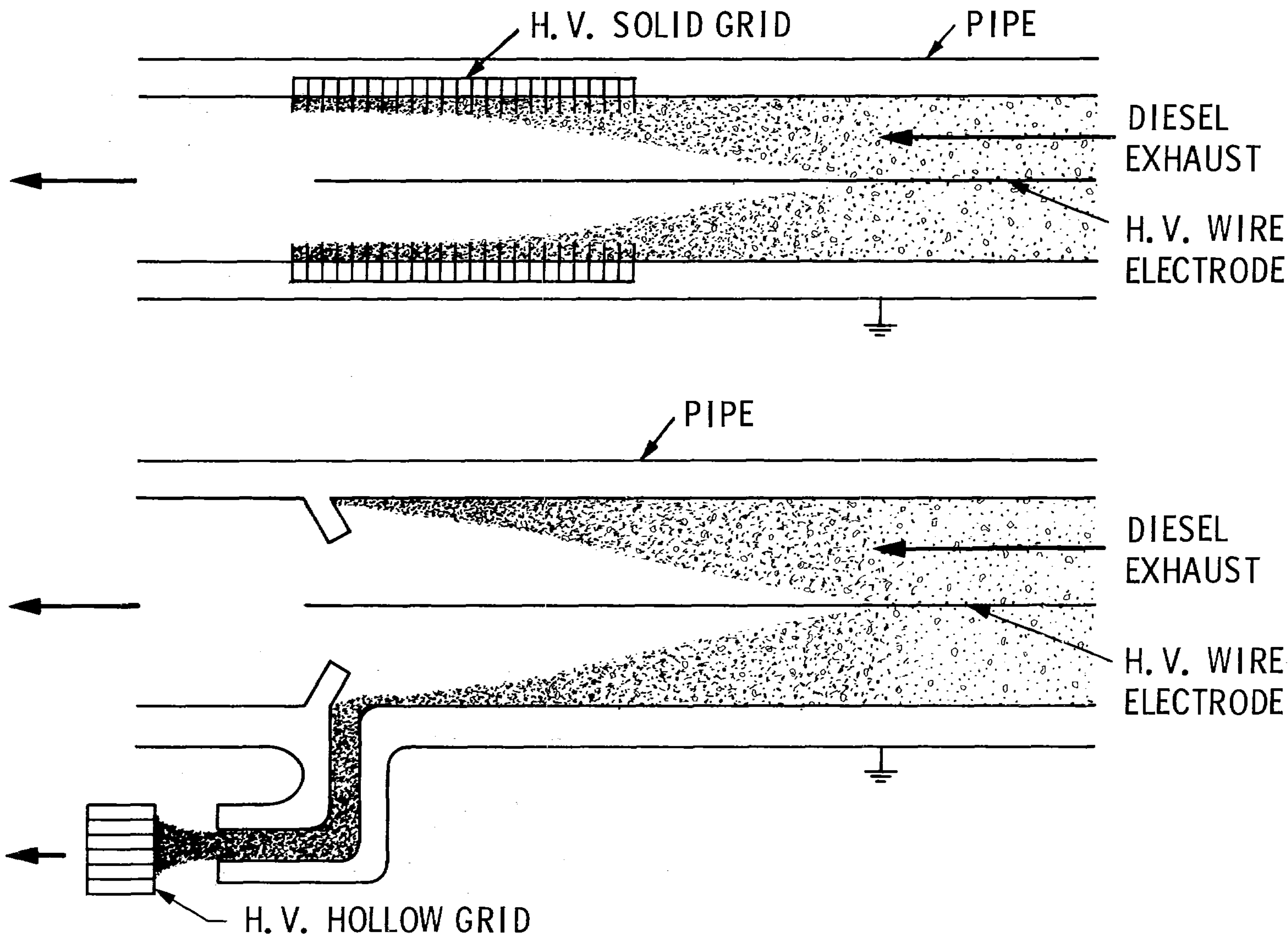


Fig. 11. Schematic Representation of an Electrostatic Precipitator for Diesel Particulates Agglomeration

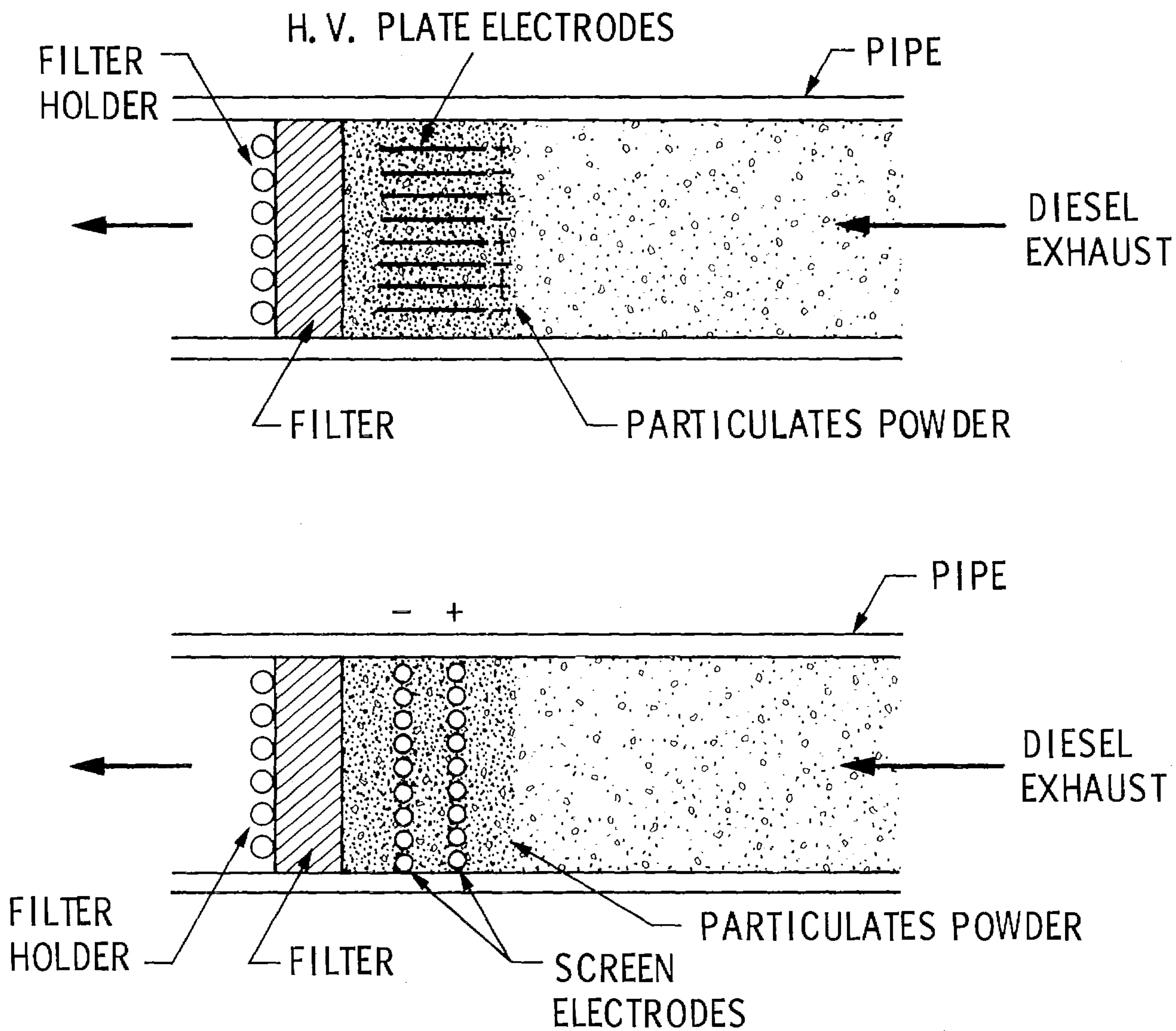


Fig. 12. Schematic Representation of an Integrated Filter-Grid Assembly

sufficiently slow flow rate, precipitation can be achieved. Thus, miniaturization will be the problem. Through private communications we have learned that both the General Motors Co. and the Ford Motor Co. are working on ESP for diesel particulates removal. The work is in the laboratory stage, but indications are that a reasonably high efficiency can be achieved.

The difficulties involved in the design of an integrated grid-filter assembly are: (1) spark erosion resistant filter material, and (2) low flow impedance requirement. Because of these problems, both ESP and integrated grid-filter techniques are complicated and obviously beyond this current project effort.

Within the allowance of the available resources, we have explored two rather simple particulates agglomeration techniques: 1) the self-release filter, and 2) fluidized bed filter. Both will be described further in detail.

3. Test Technique for Pre-Agglomeration

The pre-agglomeration is a process merely for modifying the particle size distribution. There is no accumulation of particulates on a continuous, long-term basis. Very few techniques are suitable for monitoring this information. For instance, the electrostatic aerosol analyzer (EAA) may work, but it may also perturb the particle structure (i.e. breaks up agglomerated particulates) because electrical charges are imposed on the particles. Optical counters require a relative steady-state flow of the particulates source. For the convenience of test, the charged grid can be used as a particulate indicator to monitor the number of agglomerated particulates which are large enough to generate discharge in the grid.

4. Self-Release Filter Study

The average pore size in a cordierite honeycomb diesel particulate filter is about 20μm. In other words, a large pore size filter can stop submicron diesel particulates. The process, as described in an earlier section, mainly involves self-filtering by the gradual build-up of a diesel particulate layer. It was reasoned that the same principle can be applied to a screen filter. An optimized screen mesh size may exist which at low flow pressure gradients, could maintain a filtering function for the diesel particulates. When the pressure becomes high, the agglomerated particulates could be blown off and released into the flow. The screens, being more "porous" than a cordierite ceramic, should offer a lower flow impedance. The concept can be extended to the combination of several screens and foamed metals.

Stainless screens were cut into disc forms of 7.5 cm (3 inch) in diameter and sealed to the exhaust pipe of the VW Rabbit engine via an adapter assembly. The flow aperture in the screens was 6.25 cm (2.5 inch) in diameter. The screens were held together contacting each other. A 150μm spacing grid was sealed over the downstream from the screen for monitoring the generation of large size agglomerated particulates. Some test results are summarized in Table 5.

For the coarse size screens, the pressure build-up is less severe, but also the agglomeration was less successful. Examination of the screens after prolonged operation at high back pressure showed only small amounts of particulates being retained and there were large numbers of pinholes in the particulate layer. Also visible was smoke escaping from the screen. These small amounts of collected particulates can be blown off to generate an apparent large number of spark discharges. But the overall efficiency will be

Table 5. Typical Screen Particulates Agglomeration Test Results

Screens* (or combination)	RPM	Torque ft-lb.	Time of Build-up	Pressure Build-up PSI	Pressure After Blow-Off PSI	Spark Counts at Blow-Off (10 sec)
100-200-80	1200	10	Long	3	0.5	10,600
100-200-200-80	1500	22	Long	5	1	100,000
	800	0	Long	1.5	1	220,000
100-200-200-200-80	2000	20	Long	7	2	232,000
100-200-150-80	1200	10	28 min.	5	4	-
100-150-150-80	500	5	10 min.	8	4	-
150-100	400	0	Long	6	2.5	400,000
400-80	1200	10	10 min	15	Test terminated	
508-80	1200	10	4 min	15	Test terminated	

* Flow direction was from left to right. Numbers indicated mesh number of screens.

very low. Without blow-off action, the grid counts were lower than in the case when the screens were not present in the flow. For the fine size screens, the back pressure was intolerable, but thick particulates layers were formed. Thus, a device can be designed to implement periodically inverse flow to blow the collected particulates off the screen. This type of agglomeration device is complicated and would require additional resources, therefore it was not pursued further.

5. Fluidized Bed Particulates Agglomerator

A particle bed can be used as an effective particulates filter, e.g., sand or fine beads packed on a screen with the exhaust gas flow passing through the bed toward the screen. The intrinsic flow impedance of such a filter is high, and it will increase as particulates accumulate in it. Under pressure, the bed is not fluidized so that it will be difficult to agitate it in order to release the agglomerated particulates.

However, the situation for flow in the inverse direction is entirely different. In this case, the bed can be fluidized if the flow is opposite the gravity, i.e., a gravitational fluidized bed. Also low flow impedance can be achieved. The diesel particulates will be stopped in the voids in the bed. Because the bed particles are under constant motion, these trapped and agglomerated large diesel particulates will have an opportunity to move around so as to migrate toward the downstream end of the bed and be released from the bed.

Figure 13 shows a diesel particulates agglomeration design based on such a concept. The conical section of the bed serves two purposes. First, it acts as a flow distributor and second, it provides a variable flow velocity in the cone so the desirable fluidization flow velocity will always be maintainable in the bed even though the engine exhaust is variable.

It is anticipated that in order to provide an approximate 20μm average pore size in the bed, the bed particle size required is of the order of 200 to 500μm. The critical fluidization flow velocity can be calculated as follows:

$$V_f = \frac{0.00098}{1.650\ \eta} d^2\ (\rho_b - \rho_g) \qquad \text{(Reference 7)}$$

where

d = the average diameter of the bed particles

ρ_b = density of bed particles

ρ_g = density of gas

η = viscosity of gas in centi-poise

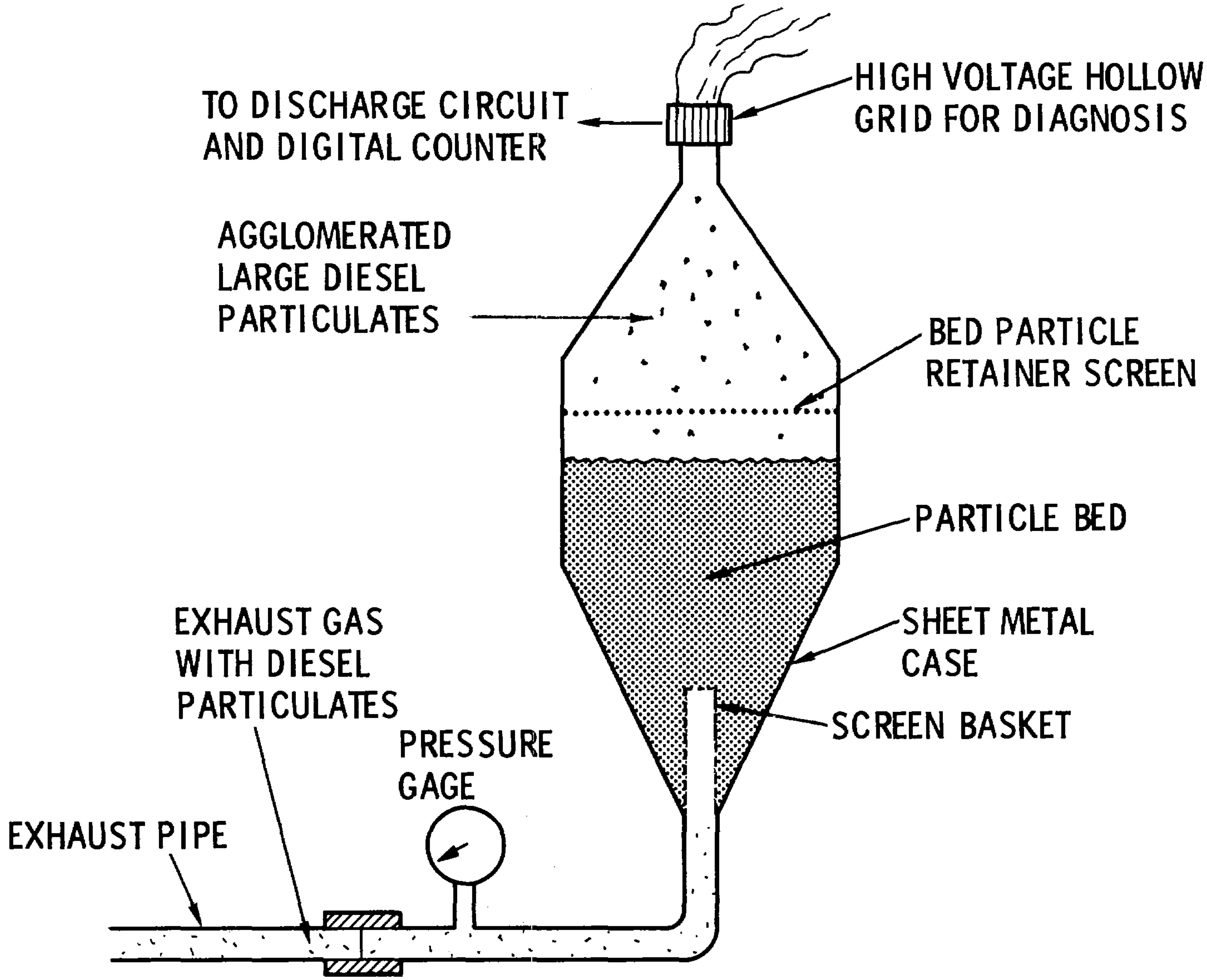


Fig. 13. Schematic Diagram of a Fluidized Bed Particulates Agglomerator

Thus by assuming

$$d = 200\ \mu m$$

$$\rho_b = 3\ g/cm^3$$

$$\rho_g \simeq 0$$

$$\eta = 0.02 \text{ centipoise for air at } 200°C$$

one can calculate to obtain

$$V_f = 3.87\ cm/s$$

The condition of a stable fluidized bed is

$$V_f < v < 10\ V_f$$

where v is the apparent flow velocity, i.e., volume flow rate divided by the cross-section area of the bed. For the maximum diameter of 25.4 cm (10 inch) of the bed shown in Figure 13, and by assuming diesel exhaust flow rate of 20 liters/s, $v \approx 60$ cm/s. Thus the bed will be operated in a slightly unstable way to provide a better agitation for the release of the agglomerated particulates. Preliminary tests of this device have shown that it is workable, however, more optimization and testing are needed before it can be successfully adopted for vehicle applications.

IX. SUMMARY AND CONCLUSION

In this project we have accomplished the following:

1. Established an understanding of the fundamental principle of diesel particulates destruction by electrical discharge.

2. Demonstrated that high destruction efficiency (~70%) can be achieved for agglomerated diesel particulates in partially optimized hardware.

3. Demonstrated that no serious amount of pollutants will be produced by this destruction technique.

4. Demonstrated that reasonably low electrical power is required for operating the device.

5. Established the basic hardware design and principle of operation.

6. Identified that the pre-agglomeration of diesel particulates is the key for successful implementation of a practical destruction device. Several agglomeration approaches have been explored.

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