Oct. 4, 1966 W. W. GARY 3,276,202

LOW TEMPERATURE AFTERBURNER

Filed May 20, 1965 2 Sheets-Sheet 1

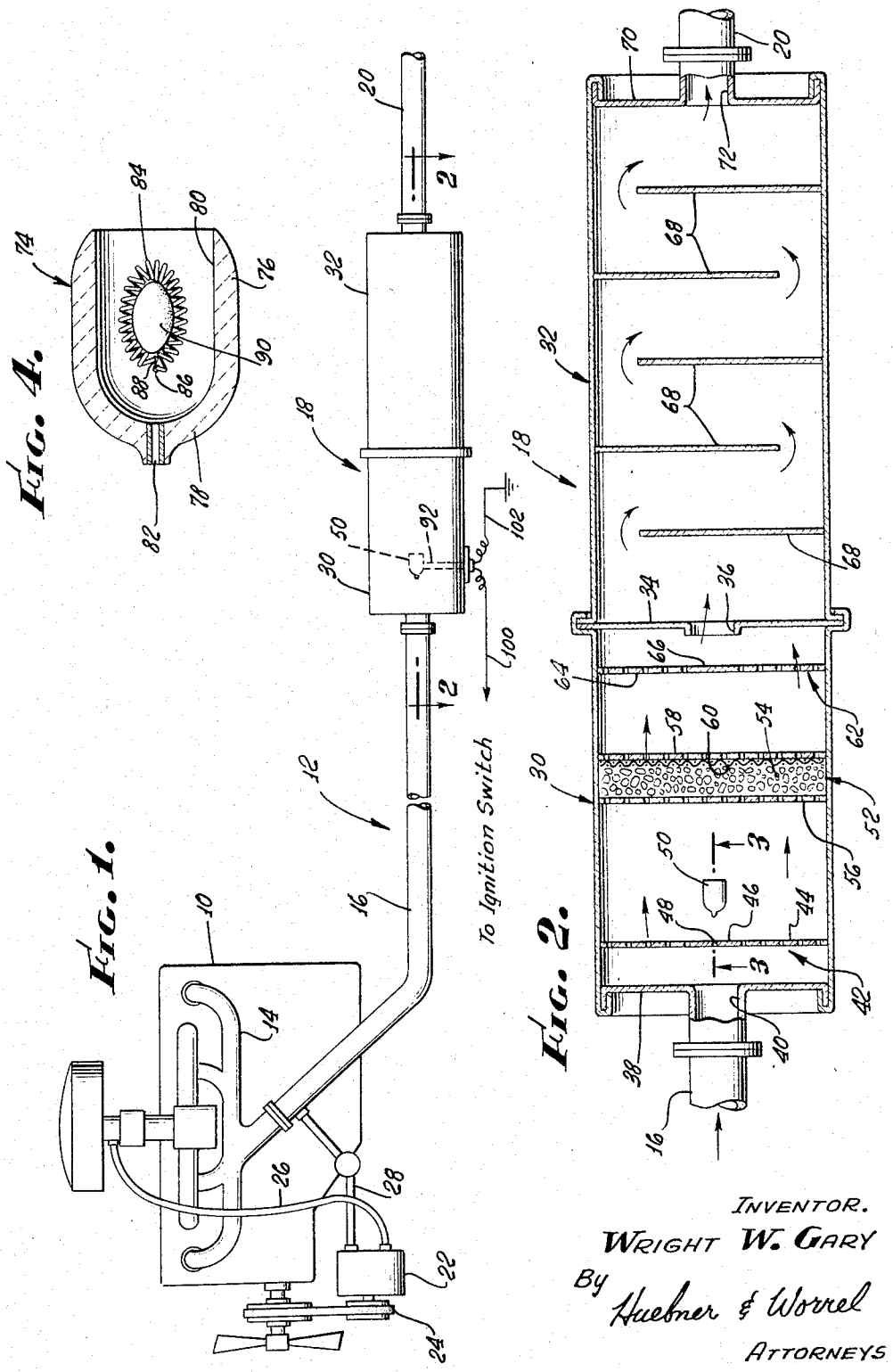

FIG. 1.

FIG. 2.

FIG. 4.

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FIG. 3.

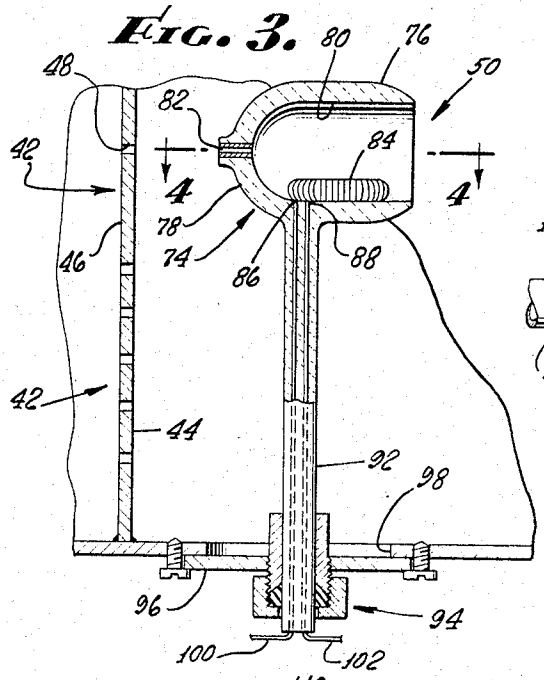


FIG. 7.

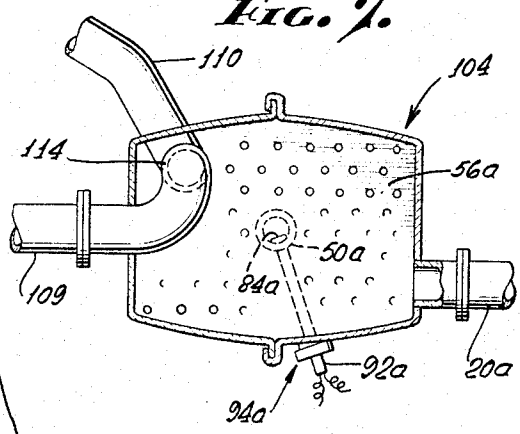


FIG. 5.

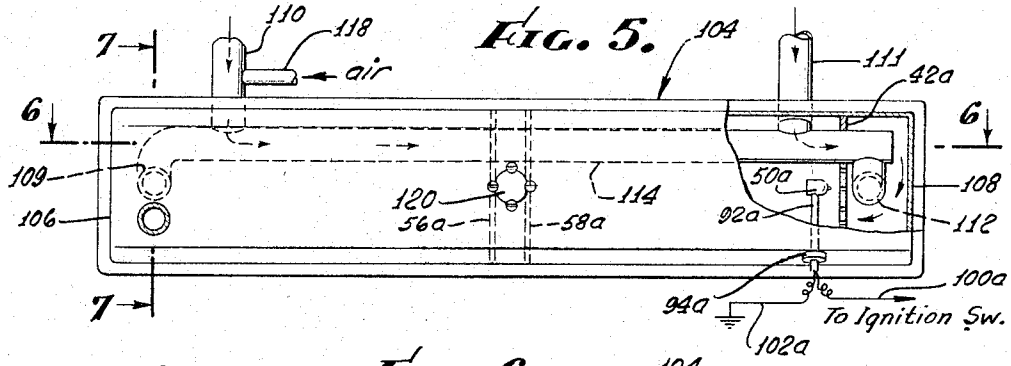
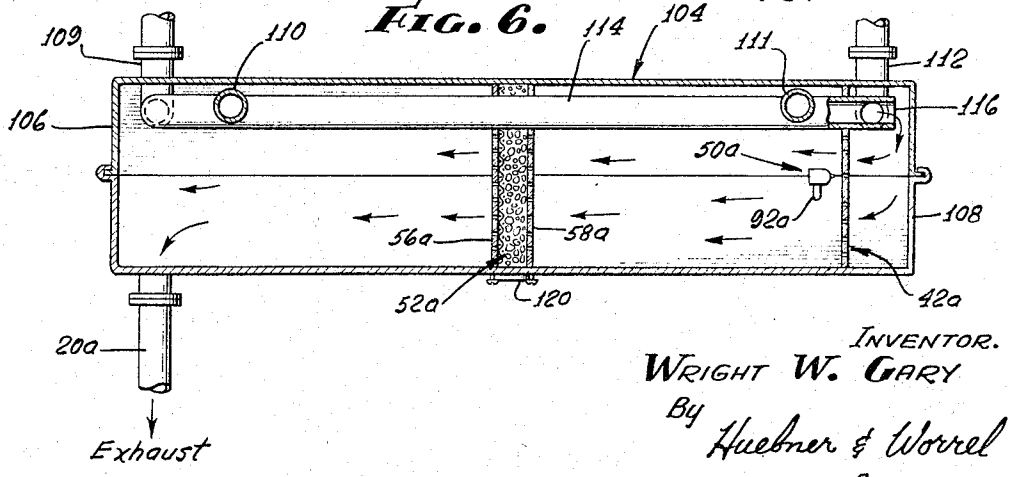


FIG. 6.



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3,276,202

LOW TEMPERATURE AFTERBURNER

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Filed May 20, 1965, Ser. No. 457,291
20 Claims. (Cl. 60—30)

The present invention relates to afterburners adapted to be employed in internal combustion engine exhaust systems for promoting the oxidation of previously unoxidized or only partially oxidized components of the exhaust gases which are harmful when released into the atmosphere, such as hydrocarbons and carbon monoxide, and the invention relates more particularly to a novel method and afterburner apparatus for obtaining this oxidation at a much lower temperature and in a smaller volume or shorter interval of time than required with previous afterburner devices.

While many devices have been developed for reducing harmful exhaust emissions from the engines of automobiles, trucks and buses, such systems can be broadly classified as either thermal combustion systems or catalytic oxidation systems. The thermal combustion systems include such apparatus as flame-type afterburners and the injection of air into the exhaust manifold at points proximate the exhaust valve ports. Such thermal combustion systems involve operation at elevated exhaust gas temperatures on the order of about 2000° F., creating difficult structural problems and likelihood of damage to equipment on the vehicle, and such systems are for the most part relatively inefficient, as will be discussed in more detail hereinafter. Catalytic oxidation systems do operate at much lower temperatures than conventional thermal combustion systems, but nevertheless are generally inefficient or ineffective at low exhaust temperatures, as during a warm-up period. Also, catalytic oxidation systems are generally relatively costly, requiring a special catalytic muffler and periodic replacement of the catalyst bed therein.

The present invention has been termed a "low temperature afterburner" because it appears to be more closely associated with the afterburner type devices than with the catalytic oxidation devices. However, the combustion is initiated at relatively low temperatures in the present invention, on the order of the temperatures connected with catalytic oxidation, by the use of a new and particularly simple structure and a novel operation which initiates the combustion by developing and exposing the exhaust stream to a sufficient population of free radicals which are formed from some of the hydrocarbon molecules in the exhaust stream.

In order to best understand the advance provided by the present invention in the air pollution control art it is necessary to discuss some of the current problems and methods and apparatus now being employed in an attempt to solve these problems.

Numerous investigations and reports have been made by authoritative engineers of the automotive industry concerning the problem of oxidizing hydrocarbons and carbon monoxide of exhaust gases after the gases have left the combustion cylinders of the engine. In order to accomplish such oxidation, it has been found necessary to (1) add air to the exhaust system, (2) conduct the oxidation at very high temperatures (or alternatively to utilize chemical catalytic action), and (3) provide a substantial volume in the exhaust system in order to allow sufficient time for the reaction to take place. With reference to (2) and (3), the higher the temperature, the smaller the volume required for a given percentage of reduction of hydrocarbon and carbon monoxide content. In order to accomplish a sufficient reduction in hydrocarbon and carbon monoxide content to satisfy official requirements,

such as the California State limitations for smog control, and at practical volume displacements in the exhaust system, temperatures of the exhaust gases to be oxidized have, with prior art afterburner devices, been required to approach 2000° F. It has heretofore been found necessary to provide relatively complicated heat exchange equipment in afterburner devices to bring the incoming exhaust up to the required combustion temperature and to cool the extremely hot oxidized exhaust gases which have the added heat that is liberated from hydrocarbon and carbon monoxide burning in the afterburner. The very high temperatures involved cause serious structural problems, even with costly modern alloy materials.

The most logical position for an afterburner, due to heat generation and space limitations in an automobile is in a position replacing the acoustic muffler. However, the farther the afterburner is placed from the engine, the cooler the exhaust gases are which enter the afterburner, and the larger and more complicated the heat exchanger that is required. Thus, the average exhaust flow through a two-inch exhaust pipe loses temperature by radiation from the outside of the exhaust pipe at a rate of approximately 100° F. per foot length of the exhaust pipe. Although many afterburner devices have been proposed to the California air pollution control authorities for approval as smog control equipment, only one afterburner device has passed the requirements, this being an afterburner device having a substantial heat exchanger therein. This afterburner passes the exhaust gases at the muffler position through a multiplicity of venturi throats which suck in sufficient air, the venturi tubes forming a heat exchanger for preheating the incoming air and exhaust mixture. Discharging from these venturi-heat exchanger tubes, the gases pass a spark plug for ignition, combustion taking place in the chamber around the venturi tubes, and the gases then pass on the outside of the venturi tubes, causing heat exchange, and then exit out the exhaust tailpipe. Under certain conditions the heat generation is so great in this device that a by-pass is required. In addition to the serious heat problem in this device, residues from the lead compounds found in nearly all gasolines sold today tend to foul the heat exchanger, cutting its efficiency, and making the incoming-air exhaust mixture more difficult to preheat to the required combustion temperature at the spark plug.

It has been found that with this one afterburner device that has been approved by the California air pollution authorities, the automobile engine must be specially tuned to a richer fuel mixture than normally required for an automobile to keep combustion adequate to pass the California specifications. This richer tuning causes about a 5% fuel penalty in miles per gallon, due to richer setting of the idle. In order to compensate for this rich idle tune, leaner jets must be placed in the carburetor for the cruising and accelerating modes. The California State Motor Vehicle Control Board in its December 16, 1964, meeting published areport estimating that due to the cost of special tuning and maintenance, an annual expenditure of $35.00 could be expected by the motorist equipped with this particular afterburner device, over and above his normal costs.

Another approach in the field of afterburners which has received a great deal of attention recently by automotive engineers is to promote oxidation of hydrocarbons and carbon monoxide by utilizing the high temperatures of the exhaust gases immediately after the gases leave the cylinder exhaust valves of the engine, by injecting the added air necessary for the combustion into the exhaust manifold proximate the exhaust valves. A report on this subject was made to the Society of Automotive Engineers, Inc., 486N, by D. A. Brownson et al., of General Motors, dated March 1962. Since it had been shown that thermal

combustion of the hydrocarbon and carbon monoxide content of the exhaust gases leaving the engine cylinders required very high temperatures, the hottest gases obviously are immediately at the exhaust valves as they open to discharge their exhaust. In fact, as each exhaust valve opens flame from the respective cylinder will discharge into the exhaust manifold. Various positions of the air discharge tube point were studied and it was found that the closer the tube outlet was to the exhaust valve, the better the result. Hence each exhaust valve requires a separate tube from an air discharge manifold. Air is provided by an air pump driven off of the engine fan belt.

Both General Motors and Ford are planning to use this system for all of their 1966 models to be sold in California, General Motors calling its system "ManAirOx," and Ford calling its system "ManOx." In the aforesaid Society of Automotive Engineers report by D. A. Brownson, at page 10, Table IV shows a comparison of the exhaust emissions with and without "ManAirOx" at that time, according to the California chassis dynamometer cycle (which will be described in some detail hereinafter). The weighted total reduction of hydrocarbon content was 14% and carbon monoxide 23% when air was injected proximate the exhaust valves, as compared with operation without the injection of air. Recent dynamometer tests with the California cycle on cars equipped with this system show a weighted average reduction of 11% for hydrocarbons and 40% for carbon monoxide, the details of the variations in hydrocarbon and carbon monoxide reduction for the various modes of vehicle operation in accordance with the California chassis dynamometer cycle being as follows:

TABLE I

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	40	55
0-25	19	50
30	29	29
30-15	33	77
15	42	26
15-30	11	25
50-20	0	71
Weighted Average	11	40

In utilizing this system, the automotive industry has found that it is necessary to use large quantities of air to accomplish satisfactory results, which requires a relatively large air pump and a correspondingly large horsepower load to drive the pump. The motor car prototypes for the 1966 models are using approximately four times the stoichiometric quantity of air that is required to burn the previously unburned hydrocarbon and carbon monoxide content of the exhaust.

However, such excessive quantities of air over the stoichiometric quantity presents another problem which has not as yet been fully explored. The California specifications do not as yet include reference to oxides of nitrogen as a criterion for limitation, but the proposed future specifications do include reference to such compounds, and it has been proven that these oxides of nitrogen are extremely harmful from a smog standpoint. The effect of excess quantities of air addition to exhaust gases was explored in a report by Dr. Nicol H. Smith, of the Franklin Institute, issued by the Air Pollution Foundation 28, dated September 14, 1959, wherein synthetic mixtures of gases were used. In general, when temperatures are high and excess oxygen is present, the formation of oxides of nitrogen is sharply increased. Therefore, it appears that the large quantities of air to be employed in the afterburner systems to be used on many of the 1966 model cars may be adding new smog hazards while reducing old ones.

It is well established that the concentration of an average automobile exhaust at about 900 parts per million hydrocarbon and an average of carbon monoxide of around 3.0% is substantially below the spontaneously ignitible range for thermal ignition unless the ignition occurs proximate the exhaust ports where the temperatures are already very high, or the temperatures of the exhaust are raised to very high levels as by means of heat exchangers. The combustion of hydrocarbons and carbon monoxide in admixture with air or oxygen and inert gases to varying degrees of dilution has been studied by many scientists for many years. A summary of some of the findings is found on page 824 of Lange's Handbook of Chemistry. Ignition temperatures of various substances and limits of inflammability of gases are tabulated. For example, hexane, one of the hydrocarbons found in exhaust gases, requires a temperature of 909° F. or above with a minimum concentration thereof of 1.3% or higher to spontaneously ignite, while carbon monoxide requires a minimum temperature of 1191° F. to 1216° F. at a minimum concentration of 6.3%. Hydrogen, which is always found in automobile exhaust gases, requires a minimum temperature of 1076° F. to 1094° F. at a minimum concentration of 6.2%. As another example, benzine, also a constituent of automotive exhaust gases, requires a minimum temperature of 1364° F. at a minimum concentration of 1.4%. When hydrocarbons in exhaust gases are expressed as parts per million, 1% represents 10,000 parts per million. It is thus readily seen that the concentration of the average automobile exhaust at about 900 parts per million hydrocarbon and about 3.0% carbon monoxide is far below the spontaneously ignitible range at normal exhaust temperatures.

According to the present invention, spontaneous combustion of previously unburned or only partially burned hydrocarbons and carbon monoxide is promoted in the exhaust conduit at relatively low temperatures by the continuous production of small quantities of free hydrocarbon radicals which carry high levels of energy, and the release of these free radicals into the exhaust stream whereupon they collide with other hydrocarbon molecules to carry out a chain reaction promoting more and more free radicals until the population of free radicals reaches the point that spontaneous combustion of substantially all combustible matter in the exhaust stream will take place. The present invention utilizes a novel reactor in the exhaust stream, and preferably but not necessarily arranged in a muffler, for generating the small initial quantity of free radicals by radiation and ionization, the small quantity of free radicals being continuously released by the reactor into the exhaust stream at all times during the operation of the internal combustion engine, with the chain reaction continuing in the exhaust stream to the point of continuous spontaneous combustion of hydrocarbons and carbon monoxide, with the result that there is a large percentage reduction of the smog-forming components in the exhaust stream without the presence of excessive temperatures and with the use of exhaust system components of normal size. Additionally, large excesses of air need not be introduced into the exhaust conduit with the present invention, and all that is required is slightly more than the stoichiometric volume. Thus, the present invention avoids problems of excessive temperature, excessively large exhaust system components and the formation of undesirable oxides of nitrogen. Nevertheless, as will be apparent from performance tables set forth hereinafter, the present invention is highly efficient in reducing hydrocarbon and carbon monoxide exhaust emissions, and brings such emissions well within the California and other official specifications.

Further objects and advantages of the present invention will appear during the course of the following part of the specification, wherein the details of construction and mode of operation of a presently preferred embodiment are de-

scribed with reference to the accompanying drawings, in which:

FIGURE 1 is a side elevation view illustrating an internal combustion engine and particularly illustrating the exhaust system thereof which embodies the present invention.

FIGURE 2 is an enlarged horizontal section taken on the line 2—2 in FIGURE 1 and illustrating the present invention embodied in a muffler.

FIGURE 3 is a further enlarged, fragmentary section taken on the line 3—3 in FIGURE 2, and illustrating details of construction and mounting of the presently preferred reactor employed in the invention.

FIGURE 4 is a sectional view taken on the line 4—4 of FIGURE 3 showing further details of the reactor.

FIGURE 5 is an elevational view of a muffler embodying the present invention and particularly adapted for use in a Volkswagen, looking from the rear of the vehicle, and with a portion of the case broken away to show internal details.

FIGURE 6 is a horizontal section taken on the line 6—6 in FIGURE 5.

FIGURE 7 is a vertical section taken on the line 7—7 in FIGURE 5.

Referring to the drawings, FIGURE 1 shows a conventional internal combustion engine **10** having an exhaust system generally designated **12** which includes exhaust manifold **14**, exhaust pipe **16** extending from manifold **14** to a muffler **18**, and a tailpipe **20** extending rearwardly from the muffler **18**.

The air that is required for oxidizing the previously unoxidized or only partially oxidized hydrocarbons and carbon monoxide in the exhaust system may be supplied by any desired means. For example, the air may be supplied by means of a small air pump or compressor **22** that is driven by the fan belt **24**, the pump **22** having an inlet conduit **26** which picks up clean air from the engine air intake system. The pump output conduit **28** is connected to the exhaust pipe **16** preferably in the upper portion thereof so that the injected air will become well mixed with the exhaust gases by the time the combination reaches the reactor of the present invention. It is preferred to embody a check valve in the conduit **28** to prevent damage to the pump by the passage of exhaust gases thereto in the event of pump or fan belt failure. One particularly desirable type of pump to use for providing air to the present exhaust system is a small pump having a slip clutch input drive as defined in my reissue patent application Serial No. 381,604, filed May 27, 1964, for "Catalytic Converter System for Internal Combustion Engines," which will issue June 1, 1965, as Reissue Patent No. 25,787. The air pump with the slip clutch drive defined in my said reissue patent provides air to the exhaust system generally in accordance with the stoichiometric requirements for the various modes of engine operation.

It is preferred in the present invention to provide air in an amount that is a little greater than the stoichiometric volume required in order to produce optimum oxidation of hydrocarbons and carbon monoxide, but the amount is much less than that which is required in systems like "ManAirOx."

I prefer to place my reactor for generating the free radicals within the muffler **18** which replaces the conventional acoustic muffler and which is substantially the same size as the conventional acoustic muffler. However, as will be apparent from the further description hereinafter, the reactor can effectively be placed at other positions in the exhaust conduit. The muffler **18** comprises two sections, an upstream afterburner section **30** and a downstream acoustic muffler section **32**. Actually, the afterburner section **30** has good acoustic properties and cooperates with the acoustic muffler section **32** to provide an acoustical muffling operation generally in accordance with accepted standards. The two sections **30** and **32** are separated by a transverse divider plate **34** having a central opening **36** therein.

The mixture of exhaust gases and air enters the afterburner section **30** through a central opening **40** in the front end plate **38** of the muffler to which the exhaust pipe **16** is connected. The gases expand in the muffler case and then pass through a transversely disposed baffle plate **42** spaced a short distance downstream from the front end plate **38**. The baffle plate **42** has a perforated peripheral portion **44** and a generally solid or imperforate center section **46**, with a small central orifice **48** therethrough.

Disposed generally on the central longitudinal axis of the muffler case a short distance downstream from the baffle plate **42**, and preferably but not necessarily in general alignment with the small central orifice **48**, is the reactor **50**. Thus, the reactor **50** is out of the main stream of flow of the exhaust gas and air mixture which is passing longitudinally through the muffler case, although the reactor **50** is assured of receiving some of the mixture because of the small central orifice **48** in the plate **42**. Details of the reactor **50** will be described hereinafter.

Spaced downstream of the reactor **50** is a heat sink **52** which extends transversely across the muffler case, and preferably comprises a porous bed of heat sink material **54** confined between a pair of transverse, axially spaced perforated retainer plates **56** and **58**. In order to prevent blanking of the holes in the downstream retainer plate **58** by the heat sink material, it is preferred to place a wire screen **60** against the upstream side of the downstream plate **58**. The bed **54** may comprise any suitable material of good heat capacity such as ceramic (alumina) balls, stainless steel wool or turnings, or any catalytic material. If the heat sink material is particulate, as with the ceramic balls or catalytic material, then is it preferred to utilize relatively large size particles, as for example ceramic balls on the order of one-half inch in diameter, so as to leave rather wide interstitial spacing. If the heat sink bed **54**, or for that matter the perforated retainer plates **56** and **58**, are not sufficiently porous, then they tend to snuff out the combustion, and particularly that of the carbon monoxide.

An automobile passes through many driving modes very quickly, and some of these modes have substantial hydrocarbon and carbon monoxide contents and at such times the oxidation causes immediate and marked temperature rise. By utilizing the heat sink, this heat is stored to assist in oxidation of hydrocarbons and carbon monoxide during other driving modes in which the concentrations of hydrocarbons and carbon monoxide are relatively low and consequently more difficult to combust. The over-all efficiency of the apparatus is consequently improved by including the heat sink, although the heat sink is not essential for operation of the invention, as will be apparent from test data set forth hereinafter. The use of a catalyst in the heat sink will normally result in an even further improvement in the efficiency of operation of the device.

Disposed transversely across the muffler case between the heat sink **52** and the divider plate **34** is a further baffle plate **62** having a perforated peripheral portion **64** and a solid or imperforate central portion **66**. The two perforated baffle plates **42** and **62** cooperate to provide a gas flow through the combustion zone of the afterburner section **30** of the muffler which is as uniform as possible in cross section. The combustion zone in the afterburner section **30** is the region immediately downstream from the reactor **50**, and even extending into and through the heat sink **52**.

The acoustic muffler section **32** may be of any conventional construction, such as the type of acoustic muffler embodying staggered acoustic baffle plates **68**. At the rear end of the acoustic section **32** is end plate **70** to which the tailpipe **20** is attached, plate **70** having an opening **72** therein through which the exhaust gases pass into the tailpipe **20**.

Referring now particularly to FIGURES 3 and 4, these figures illustrate the details of construction of a presently preferred embodiment of the reactor **50**. The reactor **50** includes a cup-shaped body **74** that is preferably made of a ceramic material resistant to thermal shock. Thus, the body **74** is of an electrical insulating material as well as a heat resistant material. The cup-shaped body **74** includes a generally cylindrical side wall portion **76** and a generally closed bottom wall portion **78** which together define a free radical generating chamber **80**. The generally cylindrical side wall portion **76** is arranged in generally coaxial relationship with the longitudinal axis of the muffler with the bottom wall portion **78** facing upstream or toward the baffle plate **42**, and with the open end of the cup **74** facing generally downstream or toward the heat sink **52**. The upstream or generally closed bottom **78** of the cup has a small orifice **82** therethrough to assure a continuous flow of the exhaust-air mixture through the reactor so as to supply hydrocarbon molecules into the reactor for the continuous production of free radicals. The size of this small orifice **82** depends upon the velocity of the exhaust gases passing the reactor cup. For example, if the reactor is placed in the normal exhaust pipe of about two inches in diameter where the exhaust-air flow is very rapid, then the orifice **82** must be very small. However, by placing the reactor in the region of enlarged cross-section within the afterburner section **30** of the muffler, having a cross-sectional area generally on the order of ten times area of the exhaust pipe, then the orifice may be larger, due to the fact that the exhaust gases are passing the reactor at only approximately one-tenth of the velocity present in the exhaust pipe. Although there is nothing critical about the size of the reactor, excellent results have been achieved employing a reactor with an inside diameter of approximately one-half inch, a depth of the hollow space in the cup of slightly over one-half inch, and an orifice close to one-sixteenth of an inch in diameter. The flow of exhaust gases around the reactor keeps a varying degree of reduced pressure in the hollow of the cup, and the exhaust gases flowing into the reactor through the orifice **82** partially satisfies this evacuation. The California criteria of modes and time of their duration gives an exhaust volume average at temperature of about 50 cubic feet per minute, and tests conducted at 50 cubic feet per minute showed a reduced pressure in the reactor in a two-inch exhaust pipe of about 1.5 inches of mercury, while in a cross-section equivalent to that of a conventional acoustic muffler the vacuum was about 0.2 inch of mercury. From various dynamometer runs with different size orifices in the two positions (exhaust pipe and muffler positions), the optimum size of orifice was found to be one which will flow on the order of 5 to 10 cubic centimeters of exhaust-air volume through the orifice per second. This results in a dwell time of the exhaust-air molecules in the generating chamber **80** of about one second, and this rate of flow appears to generate a particularly satisfactory population of free radicals to establish the chain reaction through exposure to a small electrical coil **84** placed in the hollow of the reactor. The generally imperforate center section **46** of the baffle **42** prevents the orifice **82** in the reactor from directly taking the brunt of the wide variations in exhaust flow that are axially directed into the muffler from the exhaust pipe, but the small central orifice **48** in the baffle **42** at all times provides a reasonable source of exhaust-air mixture that will flow to the reactor, with a sufficiently large orifice **82** in the reactor so that this orifice will not be susceptible to possible plugging.

In one embodiment of the invention which has proved satisfactory in test operations the electrical coil **84** comprised a helical coil made of 25 turns of 28 B and S gauge "Kanthal" resistance wire wound upon a .064 inch diameter core. This helical resistance coil was stretched to a length of slightly over one-half inch and then bent into an oval or horseshoe shape as best illustrated in FIGURE 4 of the drawings, with the terminals **86** and **88** of the coil disposed about one-eighth of an inch apart. This coil was placed against the generally cylindrical side wall **76** within the cup and cemented in place by a suitable ceramic cement that was applied in sufficiently fluid form to flow slightly between the individual turns of the helix so that upon hardening the ceramic cement fixed the location of each turn of the wire so that it could not change due to thermal distortion.

In the example of the reactor just referred to, the "Kanthal" reactor coil had a power factor of approximately 30 watts with a 12-volt battery. With this amount of electrical current flow through the coil, the amount of radiation and ionic emission from the coil was sufficient to produce excellent free radical generation per unit of gas flow through the reactor, resulting in the desired chain reaction of free radical production and the consequent spontaneous combustion of the unburned and partially burned hydrocarbons and carbon monoxide in the exhaust air-stream.

It is to be understood, of course, that any suitable resistance wire can be employed. For example, platinum wire was used in some of my early tests, and tungsten wire can also be employed. However, Kanthal, which is an iron-aluminum alloy, has a very high resistance, is relatively inexpensive and available, and will withstand temperatures over 2500° F. without degeneration. The aluminum appears to oxidize on the surface under high temperature conditions so as to form an aluminum oxide coating that protects the iron. It is desirable to include some thorium in the resistance wire of the electrical coil **84**, which will, after continued application of current to the coil, result in a thorium oxide covering of the resistance wire. It has been proven in the field of electronics that thorium oxide upon a coiled wire greatly increases the ionic flow from the wire at a given temperature, and this principle is utilized for the terminal coils of neon or "cool light" employing tungsten wire. Such increased ionic flow from the coil increases the rate of generation of the free radicals in accordance with the present invention.

It is to be understood that the coil configuration and dimensions may be varied according to the particular automotive installation to which the present invention is applied. Also, the dimensions and resistance of the wire may be varied according to the voltage of the system, so that a 6-volt system will utilize a different coil than a 12-volt system for providing the desired amount of emission and consequent free radical generation.

The reactor **50** is preferably supported by means of a ceramic stem **92** integrally connected at one end to the cup-shaped body **74** and extending therefrom generally at a right angle with respect to the axis of the cup **74**. The stem **92** extends out through the muffler case and is supported in a suitable packing gland **94** as best shown in FIGURE 3. The packing gland **94** includes a plate **96** which is removably secured to the muffler case and which covers an opening **98** in the muffler case of sufficient size to permit removal and replacement of the reactor **50** from the muffler. A pair of electrical conductors **100** and **102** extend longitudinally through the stem **92** in spaced, insulated relationship, the conductor **100** being connected to one end of the electrical coil at the terminal **86** thereof, and the conductor **102** being connected to the other end of the coil **84** at the terminal **88** thereof. The conductor **100** is connected to the vehicle battery through a suitable switching means, which for convenience is preferably the ignition switch, and the conductor **102** is grounded at a convenient location either on or near the muffler. In this way, the electrical coil **84** will be energized at all times during operation of the vehicle. By using a coil **84** which draws on the order of about 25 to 30 watts of power, the amount of power output of the coil will be approximately equivalent to that of one

headlight, and there will not be excessive load placed upon the electrical system of the vehicle. With this power output the coil will have a temperature in the general range of about 2000° F., so that a coil made of Kanthal or the like, which will withstand over 2500° F., will have a long service life.

The specific applications of the present invention to various automobile muffler systems will, of course, vary widely. The arrangement illustrated generally in FIGURES 1 to 3 is one which will be found suitable for many automobiles produced in the United States. The specific arrangement illustrated in FIGURES 5, 6 and 7 has been designed to apply the present invention to the Volkswagen, manufactured in West Germany and sold extensively in the United States, the invention here being embodied in a muffler case **104** which is adapted to replace the conventional transverse Volkswagen muffler case, and which has substantially the same over-all dimensions.

The Volkswagen muffler case **104** has end walls **106** and **108**, and entering the case **104** are four exhaust conduits **109**, **110**, **111** and **112** from the four individual cylinders of the engine. In the conventional Volkswagen muffler two of the cylinders discharge into perforated cones in the muffler, while the other two cylinders discharge into internal tubes with perforations at the ends. However, in the adaptation of the present invention to the Volkswagen muffler, all four of the exhaust conduits **109**, **110**, **111** and **112** discharged into a common manifold **114** in the muffler. The manifold **114** extends generally the length of the muffler case **104**, and the exhaust gases accumulate from the individual exhaust conduits and exit from an open end **116** of the manifold that is disposed generally adjacent to the end wall **108** of the muffler case.

The air is preferably added in this embodiment of the invention through an air conduit 118 which connects with the individual exhaust conduit **110** that in turn connects with the manifold **114** near the end opposite its opening **116**. In this way, the air and exhaust gases become thoroughly admixed by the time they leave the open end **116** of the exhaust manifold and enter the main part of the muffler case **104** near end wall **108**. Air may be provided to the conduit **118** by any convenient means, as for example by means of a small slip clutch compressor like that defined in my said Reissue Patent No. 25,787, to issue June 1, 1965, driven off of the existing engine driven belt. If desired the generator and air pump may be driven off of the same shaft, with the slip clutch drive transmitting power from the belt to both the pump and the generator. In the latter case, the present driving pulley on the generator could be smaller in diameter, and at low speeds the generator would "cut in" sooner, but at higher speeds would not exceed any predetermined rotational limit desired, because of the slippage in the slip clutch. Adjustment of the rotational limit can be accomplished by adjusting the viscosity of the silicone liquid in the slip clutch.

The Volkswagen adaptation of the invention further includes the following elements which are distributed longitudinally along the muffler case **104** in generally the same manner and which function in the same manner as the corresponding elements of the apparatus shown in FIGURES 1 to 4: a baffle plate **42***a*; a reactor **50***a* supported on a stem **92***a* which extends out of the muffler case **104** through a packing gland **94***a*; electrical conductors **100***a* and **102***a* which provide electrical current to the glow coil **84***a* in the reactor **50***a*; and a heat sink **52***a*. The only substantial structural difference between these elements and the corresponding elements in the apparatus of FIGURES 1 to 4 is that the exhaust manifold **114** passes through suitable openings in the baffle plate **42***a* and the heat sink **52***a*. Also, the spacing, sizes of the parts and electrical characteristics and the like will be varied as required to provide optimum performance, as will be the case for any specific adaptation of the invention.

The exhaust gases are vented to the atmosphere through tailpipe **20***a* that connects with the muffler case **104** near the end wall **106**. A removable loading plug **120** on the muffler case **104** permits removal and replacement of the heat sink material in the heat sink **52***a*.

In order to better understand the present invention, it is believed desirable to compare the reactor **50** of the present invention with the use of a sparkplug which is normally employed in an afterburner device, as for example in the aforesaid afterburner which is the only one as yet approved by the California authorities. In the case of a sparkplug, it operates at high discharge voltage. Therefore, it requires a coil, a condenser and a breaker, and has a time factor of high voltage accumulation. Hence, with a sparkplug there is considerable expense in appurtenances, greater battery drain than with the present reactor, and the spark is not continuous but is interrupted. With an open sparkplug in the exhaust pipe of say two inches diameter, and an average exhaust volume of 50 cubic feet per minute passing therethrough, the duration of contact time with the spark is less than .01 second, and with the lack of continuity of the spark there would not be an adequate induction period for the generation of free radicals and propagation thereof in a chain reaction. With the reactor cup of the present invention, having the small upstream orifice to pass only a relatively small volume of exhaust gases therethrough, a dwell or contact time in the reactor is established that is on the order of about one second, or approximately one hundredfold the time of an open sparkplug. This provides the necessary induction period for generation of the free radicals and creation of a chain reaction in the generation of the free radicals to the point that spontaneous combustion of the previously unburned exhaust ingredients will occur. It is to be noted that although the free radicals produced according to the present invention are hydrocarbon radicals, and such free radicals cannot be produced from carbon monoxide, nevertheless the combustion that results from the chain reaction of free hydrocarbon radicals carries the carbon monoxide with it so that carbon monoxide is also combusted.

While it is possible that free radicals might be so produced with the spark of a sparkplug if the sparking portion of the plug were placed inside an orificed cup similar to the reactor cup **74**, nevertheless the incentive to do so is not attractive due to cost, power load and the lack of continuity of the spark.

The air and exhaust gases will mix as they pass rearwardly through the exhaust conduit, but little, if any, oxidation takes place in the exhaust conduit merely because of this mixture. The average exhaust flow through a two-inch exhaust pipe loses temperature by radiation from the exhaust pipe at a rate of about 100° F. per foot length of the exhaust pipe, and with the exhaust-air mixture the temperature at a point equivalent to the muffler position will vary from about 400° F. at idle to about 1000° F. at a sustained speed of 70 miles per hour. During tests of the present invention, in order to obtain a maximum exhaust-air temperature at the reactor, the reactor was placed in the exhaust pipe about 36 inches upstream from the muffler, and samples of the exhaust were analyzed 24 inches downstream from the reactor. The result was that the reduction of hydrocarbon content was substantially zero except for the major deceleration mode of 50 to 20 miles per hour wherein a 65% reduction took place, and carbon monoxide reduction was 22%. However, during the same test there was a sample analysis taken at the tailpipe below the acoustic muffler, and the reduction of both hydrocarbon and carbon monoxide was substantial. The reduction with the use of the

reactor like reactor 50, as compared to without the use of the reactor, was as follows:

TABLE II

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	78	63
0–25	37	38
30	8	15
30–15	71	69
15	56	58
15–30	26	43
50–20	78	74
Weighted Average	38	50

The cubical volume of the exhaust pipe between the reactor and the upper sampling point that was 24 inches downstream from the reactor was only about 72 cubic inches, while the whole exhaust system below the reactor was approximately 700 cubic inches. Accordingly, the results of this test convincingly show that although the reactor started the population of free radicals, the time at the upper sampling point was insufficient to allow the chain reaction with its increasing free radical population growth to proceed to the point that would cause substantial spontaneous oxidation. However, as the reaction continued during the time allowed in the larger volume of the acoustic muffler, the chain reaction increased the population of free radicals to the point where substantial oxidation took place. While other test data set forth hereinafter will show that other locations give much higher reductions of both hydrocarbons and carbon monoxide, it is nevertheless interesting to note the comparison between the results shown in Table II and the "ManAirOx" test results shown in Table I. In this comparison the hydrocarbon reduction was over three times as effective with the reactor of the present invention than with "ManAirOx." This is important, because the hardest specification to meet in the California standards is the hydrocarbon content specification.

The performance of the present invention and comparison thereof with prior afterburner devices is best understood by reference to the official California criteria for testing automobiles. The California authorities and their technical committees studied the driving habits of the average motorist, including the times taken in the various modes, and weighted them as to their importance and duration. After extended study, the official criteria for testing automobiles were chosen as follows:

TABLE III

Mode	Cumulated Time	
	Mins., Secs.	Mins., Secs.
Idle	0 0	0 20
0–30	0 20	0 34
30	0 34	0 49
30–15	0 49	1 00
15	1 00	1 15
15–50	1 15	1 44
50–20	1 44	2 09
20–0	2 09	2 17
(This constitutes one cycle, and the next cycle immediately follows and is a duplicate of the first cycle in time, as follows:)		
Idle	2 17	2 37
0–30	2 37	2 51
30	2 51	3 06
30–15	3 06	3 17
15	3 17	3 32
15–50	3 32	4 01
50–20	4 01	4 26
20–0	4 26	4 34

At the end of the second cycle, the third is immediately commenced, followed by the fourth, fifth, sixth and seventh. Therefore, the total dynamometer test takes seven time two minutes seventeen seconds, or fifteen minutes and fifty-nine seconds. In recording the emissions of each cycle, the mode of 0 to 30 stops its emission tabulation at 25 miles per hour, and on the 15 to 50 mode it stops at 30 miles per hour. The 20 to 0 is not recorded. The fifth cycle, although run, is not recorded because the recording instruments are "zeroed" with no exhaust flow thereto from the car at that time, so that a correction factor may be made for instrument "holdup."

The official California testing requires a cold start automobile, and the first four cycles for each mode are averaged and called the "warmup period," and the last two cycles are averaged and called the "hot cycle period." Field tests and many road tests convinced the California State authorities that the final calculated car emission average would be 35% for the warmup and 65% for the hot cycle. This was partly due to the effect of the car choke in the early period of cold car operation.

One reason for describing these rather complicated criteria of the California authorities is to explain the importance of the various mode hydrocarbon and carbon monoxide reductions, because each mode in making the total passable specification is widely different in its weighting factor. The weighting for the various modes for both hydrocarbon and carbon monoxide is as follows:

TABLE IV

Weighting factor for both hydrocarbons and carbon monoxide

	Percent
Idle	4.2
0–25	24.4
30	11.8
30–15	6.2
15	5.0
15–30	45.5
50–20	2.9
	100.0

It is to be particularly noted that two acceleration modes (0 to 25 and 15 to 30) account for 69.9% of the total. Therefore, any anti-smog equipment must show good performance for these two modes in order to pass the California State specifications which allow a maximum average of 275 parts per million hydrocarbons and 1.5% carbon monoxide. Referring to the "ManAirOx" data set forth in Table I above, it is to be noted that the 0 to 25 hydrocarbon reduction was 19%, and for the heavy weighted 15 to 30 mode was only 11%. Actually, for the average used car, this is not good enough to pass the California specification. Accordingly, with the new 1966 automobiles equipped with "ManAirOx" or the like, the automobile manufacturers have been forced to lean down the fuel mixture with smaller carburetor jets, to add deceleration spark timing, etc., to get the new car hydrocarbon level as low as possible, as an adjunct to the "ManAirOx" or the like, in order to meet the specifications.

Referring to the operation of the present invention as set forth in Table II above, with the reactor disposed in the exhaust pipe ahead of the muffler, and the sampling being taken at the tailpipe below the muffler, it is to be noted that the 0 to 25 acceleration mode showed 37% reduction of hydrocarbons, and the 15 to 30 acceleration mode was 26% hydrocarbon reduction. In a further test designed to produce greater hydrocarbon reduction during these acceleration modes, the reactor was moved down the exhaust pipe to a position right at the entrance of the acoustic muffler. In the case of this test, the automobile was operated through the various cycles with the electrical switch to the coil of the reactor turned off, and emissions were taken in this way. Then the reactor was turned on, and the cycles repeated and recorded. In

this way, the reduction in emissions between the "no reactor" and "reactor" conditions could be compared in a series of sequential cycles. The results were as follows:

TABLE V

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	94	85
0–25	26	0
30	20	54
30–15	71	70
15	77	76
15–30	69	0
50–20	95	80
Weighted Average	68	50

It is to be noted that the deceleration and idle modes were very high in reductions of both hydrocarbons and carbon monoxide, but the sharp increase in over-all weighted average as specified by the California State authorities is in the 15 to 30 heavily weighted mode with 69% reduction. Although the 0 to 25 mode was some lower in the run of Table V as compared with that of Table II, the 15 to 30 mode greater efficiency was largely responsible in raising the weighted hydrocarbon efficiency from 38% reduction to 68% reduction. The weighted efficiency for carbon monoxide reduction was unchanged at 50%, although the distribution was considerably different. The two acceleration modes showed no carbon monoxide reduction with the reactor at the entrance to the acoustic muffler, but this is not a serious deficiency because these acceleration modes are consistently low in carbon monoxide emissions with the average automobile.

The reason for the much higher efficiency of the 15 to 30 acceleration mode in the test of Table V is not entirely clear, but one possible explanation might be as follows: In the upper position as shown in Table II, as the exhaust-air mixture passes the reactor and the population of free radicals is started, it was proven by the lower exhaust line sampling point that practically no oxidation or heat generation was effected until the gases reached the muffler, since the population growth had not had time to increase to the concentration required for spontaneous combustion. However, during this time lapse after passing the reactor but before reaching the muffler, the radiation from the exhaust pipe was lowering the temperature something approaching 300° F. This cooling effect may have partially broken the chain reaction of the free radicals and slowed or destroyed some of the free radicals, which then had to be "made up" after mixing in the muffler. It has been observed that if the reactor is at the inlet to the muffler, or within the muffler, the temperature rise is to a higher level than if the reactor is upstream. This is true with any muffler and particularly with a heavily insulated straight through type of muffler such as the "Glass Pack Muffler." Thus it appears that self-generated temperature through oxidation promotes either faster free radical generation, or a combination of free radical and thermal combustion, and the heat insulation qualities of the muffler assist in this build-up of higher temperature and better reaction velocity.

Since the California State cycle goes through seven different modes of operation of the vehicle during a time lapse of only two minutes seventeen seconds, the exhaust volumes at standard conditions of temperature and pressure and also at the elevated operational temperatures vary widely during the cycle. For an average car, such as a Chevrolet, Ford or Plymouth, these exhaust volumes are approximately:

TABLE VI

Standard Temp. and Pressure		Elevated Operating Temperatures	
Mode	Flow (c.f.m.)	Mode	Flow (c.f.m.)
Idle	9	Idle	18
0–25	69	0–25	188
30	27	30	70
30–15	9	30–15	22
15	14	15	34
15–30	59	15–30	162
50–20	9	50–20	24

The orifice **82** in the reactor **50** must cope with these quickly changing volumes. When the reactor is within the exhaust pipe of approximately two inches diameter, as in the example given in Table II, it is believed that the 0 to 25 and 15 to 30 modes with their very high exhaust flows tend to overload the reactor by excess flow through the orifice, causing reduction of free radical formation. This dictates that if the reactor is disposed in the exhaust pipe, the orifice size be very small to accommodate these acceleration modes, particularly since it is seen in Table IV that the weighting factor is particularly heavy for these two modes, being 24.4% for the 0 to 25 mode and 45.5% for the 15 to 30 mode. On the other hand, with such a small orifice to protect the high velocity condition of acceleration, during the idle and deceleration modes the flow into the reactor is below optimum.

The arrangement shown in the drawings wherein the reactor is disposed within the muffler case, and behind a baffle plate which prevents the flow of the exhaust gases coming out of the exhaust pipe from directly impinging on the reactor, appears to minimize this problem of obtaining approximately the correct amount of flow into the reactor under the various modes of operation. It will be apparent that placement of the reactor at different positions in the exhaust conduit, and at different positions in the muffler or in association with different muffler configurations, will provide varying results for the different modes. The important thing is to provide sufficiently efficient production of free radicals and chain reaction growth thereof to provide good combustion during the more heavily weighted modes.

Further tests were run placing the reactor in a combination combustion and acoustic muffler generally along the lines of that shown in FIGURE 2 of the drawings, but without the use of a heat sink, and with the reactor placed between a pair of baffle plates generally similar to the plates **42** and **62**. Dynamometer runs gave the following results:

TABLE VII

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	99	97
0–25	40	0
30	15	17
30–15	92	84
15	54	92
15–30	29	20
50–20	97	94
Weighted Average	59	59

Average Emissions: 241 p.p.m. hydrocarbons; 0.73% carbon monoxide.

The heat sink **52** shown in FIGURE 2 was then added, with about one-third pound of stainless steel wool form-

ing the actual bed **54** of heat sink material, and the following results were then obtained:

TABLE VIII

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	96	83
0–25	55	0
30	33	10
30–15	88	84
15	95	82
15–30	39	0
50–20	98	94
Weighted Average	66	51

It is noted that there is a substantial improvement in the acceleration modes of 0 to 25 and 15 to 30 which has resulted from the addition of this small amount of heat sink material, as shown in the results of Table VIII vs. the results of Table VII. However, it is also noted that there is a drop in the carbon monoxide reduction, which appears to occur when the heat sink is either too close to the reactor or too dense and non-porous. Variations in the heat sink as to porosity and position can be made to achieve a satisfactory balance between hydrocarbon and carbon monoxide reduction.

It is to be noted that the foregoing test results of the present invention as set forth in Tables II, V, VII and VIII give the percentage reductions of hydrocarbons and carbon monoxide for the "hot cycle period" in the California chassis dynamometer test. The following further test was made utilizing apparatus like that shown in FIGURES 1 to 4 of the drawings, wherein the heat sink included a little over a pound of a particulate catalyst material that had been employed in a catalytic muffler for more than 25,000 miles of operation, and which had lost much of its catalytic effectiveness. The details of hydrocarbon and carbon monoxide reduction for the various modes during the "hot cycle period" are set forth in Table IX below. Table X below shows the average percentage reduction figures for both the "warmup period" and the "hot cycle period," for both hydrocarbons and carbon monoxide, and also shows the weighted averages between the warmup and hot cycle periods (attributing 35% to the warmup and 65% to the hot cycle). Table XI below shows the parts per million hydrocarbons for the warmup and hot cycle periods, and the weighted average thereof, both without the present invention and with the present invention; and also the percentage of carbon monoxide in the exhaust stream both during the warmup and hot cycle periods, and the weighted average thereof, with and without the present invention.

TABLE IX

Mode	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Idle	98	71
0–25	89	0
30	71	6
30–15	92	83
15	38	25
15–30	45	29
50–20	96	84
Weighted Average	73	44

TABLE X

	Hydrocarbon Reduction, Percent	Carbon Monoxide Reduction, Percent
Warmup	57	28
Hot Cycle	73	44
Weighted Average	66	39

TABLE XI

	Hydrocarbons (parts per million)	Carbon Monoxide (percent)
Without Invention:		
Warmup	840	1.77
Hot Cycle	602	1.81
Weighted Average	686	1.80
With Invention:		
Warmup	363	1.27
Hot Cycle	161	1.02
Weighted Average	232	1.10

It is clear from the foregoing tests that the over-all weighted average is good when the present invention is employed, and is far superior to the specially tuned and equipped American automobile afterburner systems such as "ManAirOx." All of the foregoing tests of the present invention were made without any tuning and without any special deceleration and timing equipment, or lean jets in the carburetor. Furthermore, all of the tests were made on what might be considered an average automobile, a 1959 Chevrolet in the 50,000 miles age bracket.

During the extensive testing of this invention it has been found that the small orifice **82** in the reactor cup **74** does not plug or even become dirty. This is probably because the reactor is so hot during operation that none of the ingredients in the exhaust stream can stick to it; none of the tars, gums and similar organics can exist in solid form at the operational temperatures of the reactor. The lead oxide that will usually be in the exhaust stream is either in such a fine form that it will not plug the orifice, or else it is volatile when it passes the reactor.

While the instant invention has been shown and described herein in what is believed to be the most practical and preferred embodiment, it is recognized that departures may be made therefrom within the scope of the invention, which is therefore not to be limited to the details disclosed herein, but is to be accorded the full scope of the claims.

I claim:

1. The method of reducing harmful internal combustion engine exhaust emissions which comprises the steps of mixing air with the flow of exhaust gases from the engine, establishing a zone which is isolated from the main stream of flow of the exhaust air-mixture through which a small portion of said mixture slowly flows, generating a population of free radicals in said zone by converting some of the hydrocarbon molecules within said zone into free hydrocarbon radicals, and releasing said free radicals into the main stream of exhaust-air flow to promote a chain reaction of free radical generation in the main stream, which results in spontaneous combustion of hydrocarbons and carbon monoxide in the main stream.

2. The method of claim **1** wherein said free radicals are generated by electric current excitation in said zone.

3. The method of claim **2** wherein said excitation is caused by passing electric current through a resistance filament in said zone so as to heat the filament to a temperature substantially higher than the average temperature of the exhaust-air mixture.

4. The method of claim **1** wherein said free radicals are generated in said zone by the localized application of intense heat to said portion of the exhaust-air mixture in said zone.

5. The method of claim **1** which includes passing said exhaust-air mixture through a porous heat sink downstream of said zone to store heat from the mixture during modes of engine operation wherein the exhaust gases are relatively hot, said stored heat assisting in the propagation of said population of free radicals during modes of engine operation wherein the exhaust gases are relatively cool.

6. The method of claim 5 wherein said heat sink includes catalytic oxidizing material, heat generated by the free radical propagated combustion and heat stored in the heat sink producing efficient catalytic operating temperatures to further the oxidation of previously unoxidized exhaust ingredients.

7. A low temperature afterburner for an internal combustion engine exhaust system having exhaust conduit means into which air is introduced to provide an exhaust-air mixture flowing therethrough, said afterburner comprising a reactor supported in said conduit means downstream from the point of air introduction and having a generally cup-shaped body of heat resistant material defining a chamber therein, with an open end facing downstream and a generally closed bottom facing upstream, said body having an orifice through the wall thereof communicating with said chamber upstream from said open end for admitting a small portion of the flow of said exhaust-air mixture into the reactor, and means disposed within said chamber for ionizing some of the hydrocarbon molecules within said chamber so as to generate a population of free radicals in the chamber, said free radicals flowing out of said open end of the body of the reactor into the main stream of exhaust-air flow to promote a chain reaction of free radical generation in the main stream, resulting in spontaneous combustion of hydrocarbons and carbon monoxide downstream of the reactor.

8. A low temperature afterburner as defined in claim 7 wherein said reactor is composed of ceramic.

9. A low temperature afterburner as defined in claim 7 wherein said orifice extends through said bottom wall of the reactor cup.

10. A low temperature afterburner as defined in claim 9 which includes baffle plate means disposed directly upstream of said reactor and oriented generally transversely of the direction of flow of the stream, said baffle plate means diverting the main exhaust-air stream around the reactor so that the direct flow of the stream will not impinge against said orifice in the reactor.

11. A low temperature afterburner as defined in claim 10 wherein said baffle plate means has a small orifice therethrough generally in the line of exhaust-air flow with respect to said reactor so as to provide a metered supply of the exhaust-air mixture to the reactor.

12. A low temperature afterburner as defined in claim 7, wherein said ionizing means is electrically energized.

13. A low temperature afterburner as defined in claim 12 wherein said electrically energized means comprises a resistance filament supported within said chamber.

14. A low temperature afterburner as defined in claim 13, wherein said resistance filament comprises a small helical coil of resistance wire formed into a loop and secured against the side wall of the cup in said chamber.

15. A low temperature afterburner as defined in claim 7, which includes a porous heat sink disposed in said conduit downstream of said reactor.

16. A low temperature afterburner as defined in claim 15, wherein said heat sink includes catalytic oxidizing material.

17. A low temperature afterburner for an internal combustion engine exhaust system having an exhaust pipe and having air introduction means to provide an exhaust-air mixture flowing through at least a portion of said exhaust pipe, said afterburner comprising a muffler case having an inlet connected to said exhaust pipe and having an outlet, said muffler case including wall means defining a flow path for the exhaust-air mixture from said inlet to said outlet, and a reactor mounted within said case in the flow path and having a generally cup-shaped body of heat resistant material defining a free radical generating chamber therein, with an open end facing downstream and a generally closed bottom facing upstream, said body having an orifice through the wall thereof communicating with said chamber upstream from said open end for admitting a small portion of the flow of said exhaust-air mixture into the reactor, electrically energized means disposed within said generating chamber for ionizing some of the hydrocarbon molecules within the generating chamber so as to generate a population of free radicals therein, said free radicals flowing out of said open end of the reactor body into the main stream of exhaust-air flow through said flow path to promote a chain reaction of free radical generation in the main stream, resulting in spontaneous combustion of hydrocarbons and carbon monoxide downstream of the reactor, said flow path in the muffler extending a substantial distance downstream of said reactor and providing a combustion chamber within the muffler immediately downstream of the reactor within which said chain reaction and spontaneous combustion occur.

18. A low temperature afterburner as defined in claim 17 wherein said flow path within the muffler proximate the reactor and in the region of said combustion chamber has a cross-sectional area that is substantially greater than that of the exhaust pipe and that of the reactor.

19. A low temperature afterburner as defined in claim 18 which includes baffle plate means supported in the muffler case and arranged in said flow path, oriented generally transversely to the direction of flow through the flow path, and interposed between said inlet and the reactor so as to divert the main exhaust-air stream around the reactor so that the direct flow of the stream will not impinge against the reactor.

20. A low temperature afterburner as defined in claim 18 which includes a porous heat sink in said combustion chamber in the flow path, said heat sink being spaced downstream from the reactor.

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