(54) **Title:** METHOD AND APPARATUS FOR TESTING CATALYTIC CONVERTER DURABILITY

(57) **Abstract:** The present application relates in general to an apparatus (1) and to methods for testing the performance of an automotive catalytic converter (170) under conditions simulating those which occur in motor vehicles over extended driving conditions. The applications provides a novel swirl plate (18) for creating a flow pattern involving the interaction of a number of swirl jets (242). The interaction of the swirl jets (242) creates a swirl flow that collapses and expands, preferably at intervals that are substantially equivalent in length to the inner diameter of a combustion tube (210). The swirl plate (18) and a fuel injector (16) enable the burner to run stoichiometric for extended periods of time.

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TITLE: METHOD AND APPARATUS FOR TESTING CATALYTIC CONVERTER DURABILITY

Priority Data

[0001] The present application claims the benefit of provisional application Serial No. 60/310,345, filed August 6, 2001, which is incorporated herein by reference.

Field of the Invention

[0002] The present application relates in general to an apparatus and to methods for testing the performance of an automotive catalytic converter under conditions simulating those which occur in motor vehicles over extended driving conditions.

Background

[0003] An automotive catalytic converter is an emissions control device which may be incorporated into the exhaust system of a motor vehicle between the exhaust manifold and the muffler. The catalytic converter contains one or more catalysts , such as those based on platinum, palladium, or rhodium, which reduce the levels of hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) in the exhaust gas, thereby reducing the amount of these pollutants which would otherwise be emitted into the atmosphere from the vehicle. In a typical commercial catalytic converter, HC and CO in the exhaust are oxidized to form carbon dioxide (CO2) and water, and NOx is reduced to nitrogen, carbon dioxide, and water.

[0004] As a result of recent regulatory initiatives, motor vehicle emissions control devices, including catalytic converters, are now required to have longer useful lives. For example the US Environmental Protection Agency (EPA) in 1996 in 40 C.F.R. 86.094-2

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increased the mileage for which automotive emission control elements must function

from 50,000 to 100,000 vehicle miles. This requirement places severe demands on a

catalytic converter, since a number of components introduced into the typical automotive

internal combustion engine exhaust can act as a poison to the catalyst present in the

5   converter.

[0005] In order to understand the effects of potential catalytic converter catalyst poisons,

it is necessary to have a testing apparatus and procedure that will permit the evaluation of

the long term effects of the individual variables which may affect the performance of the

catalyst. Historically, an internal combustion engine has been used for such an

10   evaluation, however, such an apparatus can be inconsistent, maintenance intensive, and

expensive to operate. In addition, such an apparatus does not conveniently permit the

separate evaluation of individual variables, such as the effects of constituents of the fuel

and of constituents of the oil. Also, the engine oil consumption varies with engine age,

operating temperature, speed and other variables, which are difficult to control.

15   [0006] A test apparatus and testing method are needed which overcome the foregoing

deficiencies.

Summary of the Invention

[0007] In one aspect, the application provides an apparatus for aging a catalytic

20   converter comprising: catalytic converter means; combustion means in fluid

communication with said catalytic converter means; fuel injection means in fluid

communication with said combustion means; and lubricant injection means in fluid

communication with said catalytic converter means. The apparatus also preferably

comprises: data acquisition means; air supply means in fluid communication with said combustion means; and, heat exchanger means in fluid communication with said combustion means.

[0008] In another aspect, the application provides an apparatus for aging a catalytic

5   converter comprising: a burner adapted to provide substantially continuous stoichiometric combustion of a feedstream and to produce an exhaust product; a fuel injector system in fluid communication with said burner; a catalytic converter in fluid communication with said exhaust product; and, a lubricant injection system in fluid communication with said catalytic converter. In a preferred embodiment, the apparatus also comprises a data

10   acquisition system adapted to provide substantially continuous fuel metering control, and preferably substantially continuous catalyst safety monitoring.

[0009] Preferably, the burner comprises a swirl plate means. In a preferred embodiment, the swirl plate means is a swirl stabilized burner. The swirl stabilized burner preferably comprises: a plenum chamber; a combustion tube; and, a swirl plate separating said

15   plenum chamber and said combustion tube comprising an air assisted fuel spray nozzle assembly means.

[0010] In another aspect, the swirl stabilized burner comprises: a plenum chamber; a combustion tube defining a bore; and, a swirl plate separating said plenum chamber and said combustion tube, said swirl plate being adapted to produce a pattern of collapsed

20   conical and swirl flow in said combustion tube that defines at least one flow path along said bore, preferably at least three flowpaths. In this embodiment, the swirl plate preferably comprises an air assisted fuel spray nozzle assembly in fluid communication

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with an air supply and a fuel supply. The air supply and fuel supply preferably are

adapted to provide atomized fuel to said combustion means. The pattern produced by the

swirl plate preferably collapses and expands at intervals that are substantially equal to the

inner diameter of the burner. In the embodiment described herein, the inner diameter of

5   the burner is about 4 inches, and the pattern produced by the swirl plate preferably

collapses and expands at intervals of about 4 inches. The apparatus preferably comprises

at least one igniter in fluid communication with said at least one flowpath, preferably at

least one igniter in fluid communication with each of three flowpaths. The lubricant

injection system preferably is adapted to provide an atomized spray of lubricant

10   comprising droplets having a sufficiently small diameter to vaporize upon exposure to

said burner. In a preferred embodiment, the diameter of the droplets is about 80 microns

or less, preferably about 20 microns or less.

[0011] In another aspect, the application provides a burner for producing continuous

stoichiometric combustion of automotive fuel. The burner comprises: a plenum

15   chamber; a combustion tube; a swirl plate separating said plenum chamber and said

combustion tube comprising an air assisted fuel spray nozzle assembly means. A

preferred burner is the swirl stablized burner, described above.

Brief Description of the Figures

20   [0012] Figure 1 shows a schematic diagram of one embodiment of the system.

[0013] Figure 2A is a drawing of a preferred embodiment of a burner suitable for use

with the present application.

[0014] Figure 2B is a close up view of the circled portion of the burner.

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[0015] Figures 3A is a frontal view of a swirl plate which imparts the desired swirling

motion to the air entering the combustion section of the burner.

[0016] Figure 3C is a rear view of the swirl plate of Figure 3A.

[0017] Figures 3B, 3D, and 3E are cross sections through the swirl plate of Figures 3A

5   and 3C.

[0018] Figures 4A is a cutaway view depicting a preferred embodiment of a heat

exchanger suitable for use with the present application.

[0019] Figure 4B is a cutaway view of another section of the heat exchanger at

approximately a 90° angle to the view in Figure 4A.

10   [0020] Figure 5A is an exploded view of one embodiment of an air assisted fuel spray

nozzle suitable for use in the apparatus.

[0021] Figure 5B is a frontal view of the flanged end of the male fitting of the air

assisted fuel spray nozzle of Figure 5A illustrating an arrangement of air injection

openings.

15   [0022] Figure 5C is a frontal view of the opposed end of the air assisted fuel spray

nozzle of Figure 5B.

[0023] Figure 5D is an illustration of a preferred air assisted fuel spray nozzle.

[0024] Figure 5E is a frontal view of the flanged end of the male fitting of the air

assisted fuel spray nozzle of Figure 5D.

20   [0025] Figure 5F is a frontal view of the opposed end of the air assisted fuel spray nozzle

of Figure 5D.

[0026] Figure 6A is a drawing depicting a preferred embodiment of an oil injection

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system suitable for use with the present application.

[0027] Figure 6B is an exploded view of the oil injection nozzle from Figure 6A.

[0028] Fig. 7 is a block diagram of a data acqusition and control system suitable for use in the system.

[0029] Figure 8 is a chart of droplet trajectories for various size droplets in a droplet distribution with an SMD of 20 microns (Example 1).

[0030] Figure 9 is a graph showing measured, raw exhaust gas concentrations for the present system (50 SCFM) and a Ford 4.6L, V-8 engine (50 SCFM, 1500 rpm, 90 lb-ft, no EGR), both operating on the same batch of CA Phase II fuel, at a slightly lean and a slightly rich exhaust A/F.

[0031] Figure 10 is a schematic of a closed-loop fan control logic for maintaining the catalyst inlet temperature.

[0032] Figure 11 shows a RAT-A simulation on FOCAS™ compared to an engine.

[0033] Figure 12 shows a comparison of the FTP performance degradation for average engine and burner aged catalysts.

[0034] Figure 13 shows THC conversion efficiency, as measured by an engine-based catalyst performance evaluation rig, for unaged and aged catalysts.

[0035] Figure 14 is a speed versus time illustration of the 505 and the 867 phases of the FTP driving cycle.

[0036] Figure 15 illustrates modal THC emissions before and after aging.

[0037] Figure 16 illustrates average FTP emissions, grouped by catalyst and age.

[0038] Figure 17 illustrates a comparison of the FTP performance degradation for the

average engine and burner aged catalysts.

[0039] Figure 18 illustrates the front panel control software for the burner system.

[0040] Figure 19 illustrates the catalyst bed temperatures during RAT-A cycle operation on the engine stand and on the burner rig.

[0041] Figure 20 illustrates a schematic of prediction for impact of fuel/air stream with burner wall.

[0042] Figure 21 illustrates a calculation of fuel spray impact on burner wall as a function of air assist angle of injection.

[0043] Figure 22 illustrates cold-start, bag-1 results: burner and engine aged catalysts.

[0044] Figure 23 illustrates accumulated THC mass during cold-start, before and after aging.

[0045] Figure 24 illustrates accumulated NO_x mass during cold-start, before and after aging.

[0046] Figure 25 illustrates THC emissions by aging type, catalyst, and aging hours.

[0047] Figure 26 illustrates NMHC emissions by aging type, catalyst, and aging hours.

[0048] Figure 27 illustrates NO_x emissions by aging type, catalyst, and aging hours.

[0049] Figure 28 illustrates CO emissions by aging type, catalyst, and aging hours.

[0050] Figure 29 shows the measured mass emission during the cold-start phase of the FTP.

Brief Description

[0051] The application provides a test apparatus which produces a simulated exhaust gas with a composition and temperature corresponding to that produced by the internal

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combustion engine of a motor vehicle. The apparatus can be used with or without using

lubricating oil in its operation. Precise amounts of lubricating oil can be added to the

exhaust gas if required. The apparatus and method are suitable for aging of an

automotive catalytic converter or, if desired, a small scale core catalytic converter over

5   simulated extended driving conditions. The apparatus quickly and accurately produces

the effects of additives and contaminants from the engine fuel and/or lubricant oil on the

durability of a full scale catalytic converter over simulated periods of extended operation.

The apparatus is capable of producing an aged converter catalyst which can be

performance tested on an actual vehicle.

10   [0052] As used herein the term "automotive catalytic converter" or "catalytic converter"

means a full scale emissions control device suitable for incorporation into the exhaust

system of a motor vehicle between the exhaust manifold and the muffler. As used herein

the term "extended driving conditions" means at least 50,000 vehicle miles, and more

preferably at least 100,000 vehicle miles.

15   [0053] As will be demonstrated herein, the present application allows for simultaneously

or separately determining the effects of additives and contaminants in automotive fuel

and in lubricant oil on the durability of a catalytic converter over simulated periods of

extended driving conditions. In addition, the application is capable of producing an aged

catalytic converter catalyst suitable for performance testing on an actual vehicle.

20   [0054] Various components of automotive fuel and lubricant oil may contribute to

deterioration, or poisoning, of the catalyst in a catalytic converter. For example, it is well

known that leaded gasoline can cause catalyst poisoning, since the tetraethyl lead which

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has been added to the gasoline as an antiknock compound is a known catalyst poison. In

addition, other components of the fuel and lubricant system of an internal combustion

engine may act as catalyst poisons if they pass through the engine and become a

constituent of the exhaust. For example, if sulfur is present in the fuel, it will likely be

5   present as a catalyst poison in the exhaust. In addition, phosphorus and zinc, if present in

the engine lubricant oil, may be present in the exhaust and act as catalyst poisons.

[0055] The application provides a unique apparatus, and method of using same, which is

capable of separating the effects of fuel and oil, allowing precise control of each variable.

The application provides an oil free exhaust from combustion of gasoline or other fuel,

10   such as gasoline; synthetic gasoline; diesel; liquefied fuel produced from coal, peat or

similar materials; methanol; compressed natural gas; or liquefied petroleum gas. The

exhaust is provided with precise air to fuel ratio control, and a separate oil atomization

system for definitive isolation of the effects of fuel and of lubricant at various

consumption rates and states of oxidation. The apparatus is capable of operating over a

15   variety of conditions, allowing various modes of engine operation to be simulated, for

example cold start, steady state stoichiometric, lean, rich, cyclic perturbation, etc.

[0056] The apparatus comprises: (1) an air supply system to provide air for combustion

to the burner, (2) a fuel system to provide fuel to the burner, (3) a burner system to

combust the air and fuel mixture and provide the proper exhaust gas constituents, (4) a

20   heat exchanger to control the exhaust gas temperature, (5) an oil injection system, and (6)

a computerized control system.

The Air Supply System

[0057] Referring now to the drawings and initially to Figure 1, a schematic diagram of the system is shown. An air blower 30 draws ambient air through an inlet air filter 20 and exhausts a pressurized stream of air. The air blower 30 and the mass air flow sensor 50 may be of any conventional design which will be well known to a person of ordinary skill in the art. In a preferred embodiment the air blower 30 is an electric centrifugal blower, such as a Fuji Electric Model VFC404A Ring Blower, and the mass air flow sensor 50 is an automotive inlet air flow sensor such as a Bosh Model Number 0280214001 available from most retail automotive parts stores. The volume of air supplied is set by adjusting a bypass valve 40 to produce a desired flow rate of air, which is measured by a mass flow sensor 50.

The Fuel Supply System

[0058] A standard automotive fuel pump 10 pumps automotive fuel through a fuel line 12 to an electronically actuated fuel control valve 14 then to the burner 60 (described in more detail below). As used herein, the term "automotive fuel" means any substance which may be used as a fuel for the internal combustion engine of a motor vehicle, including, but not necessarily limited to, gasoline; synthetic gasoline; diesel; liquefied fuel produced from coal, peat or similar materials; methanol; compressed natural gas; or liquefied petroleum gas.

[0059] Although other types of control valves may be used, a preferred fuel control valve 14 is a solenoid valve that receives a pulse width modulated signal from the computer control system and regulates the flow of fuel to the burner in proportion to the pulse

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width. The electronically actuated solenoid valve 14 may be of a design which will

operate with a pulse modulated signal which will be well known to a person of ordinary

skill in the art. In a preferred embodiment the electronically actuated fuel control valve

14 is a Bosch frequency valve model number 0280 150 306-850 available from most

5   retail automotive parts suppliers. From the fuel control valve 14 the fuel is piped to the air

assisted fuel spray nozzle 16 in the burner assembly (described below).

The Burner

[0060] The burner is specially fabricated, as described below to produce stoichiometric

combustion of the fuel and air. In a preferred embodiment, the burner 60 is a swirl

10   stabilized burner capable of producing continuous stoichiometric combustion of

automotive fuel.

[0061] Referring now to Figure 2, in a preferred embodiment the burner comprises a

plenum chamber 200 and a combustion tube 210. A swirl plate 18 separates the plenum

chamber 200 from the combustion tube 210. The combustion tube 210 is constructed of

15   material capable of withstanding extremely high temperatures. Preferred materials

include, but are not necessarily limited to INCONEL or stainless steel, and optionally can

be equipped with a quartz tube in place of the INCONEL tube for visual observation of

the resulting flame pattern.

[0062] The air and fuel are separately introduced into the burner 60. Air from the mass

20   flow sensor 50 is ducted to the plenum chamber 200 (Fig. 2) then through the swirl plate

18 into the burner tube. The swirl plate 18 is equipped with a fuel injector 16.

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-Fuel injector

[0063]   In a first embodiment, an air assisted fuel spray nozzle 16 is engaged using conventional means at the center of the swirl plate 18 inside of the plenum chamber 200 (Fig. 2). Fuel from the fuel supply line 14 is fed to the air assist fuel spray nozzle 16,

5   where it is mixed with compressed air from air line 15 and sprayed into the combustion tube 210 (Fig. 2). The compressed air line 15 provides high pressure air to assist in fuel atomization.

[0064]   Fig. 5A is one embodiment of the air assisted fuel spray nozzle 16. As seen from Fig. 5A, the air assisted fuel spray nozzle 16 comprises male and female flanged fittings

10   which are engaged with the swirl plate 18. A variety of suitable methods of engagement are known to persons of ordinary skill in the art. The female fitting 250 has a flanged end 252 and a substantially tubular extension 251. A male fitting 254 comprises a flanged end 256 and a substantially cylindrical extension 253 having an opposed end 268. The cylindrical extension fits within the tubular extension of the female fitting along its

15   length. In a preferred embodiment, the clearance 270 between the inner wall 259 of the tubular extension 251 and the outer wall 263 of the tubular extension 253 is preferably about 1/8." The clearance creates a circumferential groove 257 for injection of fuel, which communicates with the fuel injection hole 264.

[0065]   Air injection bores 262 (preferably about 1/16") extend through the flanged end

20   256 and substantially parallel to the axis of the tubular extension 253 of the male fitting to a bore 260, which interfaces with the swirl plate 18. Fuel injection bores 264 extend from the outer wall 263 adjacent to the air injection bores 262 and radially inward. The

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air injection bores 262 are engaged with the air line 15 in any suitable manner. The fuel

injection bores 264 are engaged with the fuel line 12 in any suitable manner.

[0066] Fig. 5B is a frontal view of the flanged end 254 of the male fitting illustrating an

arrangement of air injection bores 262. As seen in Fig. 5B, five air injection bores 262a-d

5   and 265 are arranged similar to the numeral "5" on a game die. Specifically, a line drawn

through the center of the central air hole 265 and through the center of any one of the

corner air holes 262 a-d will have 45° angle when compared to a line drawn along 5x-5x

in Fig. 5B. In other words, the center of the corner air holes 262a-d are found at the four

corners of a square drawn around the central air hole 265.

10   [0067] A frontal view of the opposed end of all parts of the air assist nozzle 16 when

engaged is shown in Fig. 5C. In this "bulls-eye" view: the inner circle is the bore 260 of

the female fitting; the next concentric ring is the opposed end 268 of the tubular extension

253 of the male fitting; the next concentric ring is the annular groove 270 formed by the

clearance between the tubular extension 251 of the female fitting and the extension 253 of

15   the male fitting; and, the outermost ring is the flange 252 defining a port 255.

[0068] In a preferred embodiment of the fuel injector 16 (Fig. 5D-F), like parts are given

like numbering as in Figs. 5A-5C. Referring to Fig. 5D, the air injection bores 262 are

angled to direct the fuel into the air shroud for mixing and protection, while shearing the

fuel fed through fuel injection bores 264 with injected air that passes directly through the

20   fuel jet. The fuel injection bores 264 preferably are pointed directly into the air shroud

for mixing and protection. The injection angles maximize fuel atomization within the

space requirements and work with the swirl plate 18.

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[0069] The air assisted fuel spray nozzle 16 is engaged using conventional means at the center of the swirl plate 18. The air assisted fuel spray nozzle 16 comprises a flanged male fitting 252 adapted to mate with the a central bore 244 (Fig. 3C) in the swirl plate 18. In a preferred embodiment, the concentric clearance 270 between the outer wall 254a

5   of the air assisted spray nozzle and the wall 281 of the central bore of the swirl plate 18 is preferably from about 0.2" to about 0.75", most preferably about 0.25". The air assisted fuel spray nozzle 16 defines air injection bores 262 having a longitudinal axis represented by line Y-Y'. Line Y-Y' forms angles x, x' relative to line 5F-5F, drawn along the inner wall 280 of the swirl plate. The angles x, x' preferably are from about 65° to about 80°,

10   preferably about 76°. The air injection bores 262 may have substantially any configuration. In a preferred configuration, the air injection bores 262 are cylindrical bores.

[0070] The air injection bores 262 extend from a supply end 298 to an injection end 299, and have an inner diameter effective to permit a suitable flow of fuel. In a preferred

15   embodiment, the air injection bores 262 have an inner diameter of from about 0.060" to about 0.080", preferably about 0.070". The air injection bores 262 extend from supply end 298 to the combustion tube 210 (Fig. 2) on the injection end 299.

[0071] The air assisted fuel spray nozzle 16 comprises a first flanged end 252a adapted to mate with the outer wall 282 of the swirl plate 18. The alignment of the first flanged

20   end 252a and the outer wall 282 may take a number of configurations, such as complimentary grooves, complimentary angles, or other types of mated machine fittings. In a preferred embodiment, the first flanged end 252a and the outer wall 282 are

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substantially flat and parallel to one another, abutting one another along a line

substantially perpendicular to longitudinal axis A-B. In a preferred embodiment, the first

flanged end 252a extends radially outward from the longitudinal axis, illustrated by line

A-B, to a distance of from about 0.38" to about 0.65", preferably to a distance of about

5   0.38" therefrom.

[0072] A second flanged end is not entirely necessary; however, in a preferred

embodiment, the air assisted spray nozzle 16 further comprises a second flanged end

252b extending radially outward from the longitudinal axis defined by line A-B to a

distance of from about 0.3" to about 0.45", preferably about 0.38" therefrom.

10 [0073] As shown in Fig. 5D, the first flanged end 252a and the second flanged end 252b

define a flow chamber 297 comprising a port 255 at the supply end 298. The

configuration and size of this port 255 is not critical provided that the port 255 permits

the flow of an adequate amount of fuel through the flow chamber 297 to the fuel injection

bores 264 defined by the air assisted spray nozzle 16.   The injection end 299 of the air

15 assisted spray nozzle 16 defines the fuel injection bores 264, which extend from the flow

chamber 297 to an opening 291 in the air injection bores 262. The fuel injection bores

264 may have substantially any configuration as long as they deliver an adequate flow of

fuel. The fuel injection bores 264 have a longitudinal axis represented by the line R-R',

which forms angles z, z' relative to the line 5F-5F. In a preferred embodiment, the fuel

20 injection bores 264 are cylindrical and have a diameter of from about 0.020" to about

0.040", preferably about 0.031". Preferably, angles z,z' are from about 60° to about 80°,

preferably about 73°.

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[0074] In operation, fuel flows through the port 255, through the flow chamber 297, and through the fuel injection bores 264 and opening 291, and is injected into the air injection bores 262, which results in a concurrent injection of air and fuel at the injection end 299 of the air assisted fuel spray nozzle 16. Fuel collides with air at opening 291, resulting in

5   flow jets effective to collide with the air shroud. Materials of construction and dimensions for all components of spray nozzle 16 will vary based on the process operating conditions.

[0075] As shown in Fig. 5E, the air injection bores 262 comprise openings 262a-d at the injection end 299 which are arranged like the numeral "4" on a game die. The openings

10   262 a-d preferably are spaced at approximately 90° angles relative to one another, as illustrated by AB and A'B'.

[0076] Fig. 5F is a frontal view of the supply end 298 of the air assisted fuel spray nozzle 16. In this "bulls-eye" view: the inner circle is the bore 260 and the remaining concentric rings comprise the outer face 261 of the second flanged end 252b. Fuel flows

15   from the fuel line 12 to the spray nozzle 16 through the port 255, into the fuel flow chamber 297 and through the fuel injection bores 264 to the air injection bores 262.

-Swirl plate

[0077] In a preferred embodiment the swirl plate 18 is capable of producing highly

20   turbulent swirling combustion, as shown in Figures 3A-E so as to provide a complex pattern of collapsed conical and swirl flow in the combustion area. The flow pattern created by the swirl plate 18 involves the interaction of a number of swirl jets 242 and

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242a-c, 253 and 253a-c and turbulent jets 248 and 248a-c, 249 and 249a-c, and 250 and 250a-c. The interaction of these jets creates a swirling flow that collapses and expands, preferably at intervals that are substantially equivalent in length to the inner diameter of the combustion tube 210. In a preferred embodiment, the inner diameter of the

5   combustion tube 210 is 4 inches, and the intervals at which the swirling flow collapses and expands is every 4 inches. The pattern clearly defines flow paths along the wall of the combustion tube 210, which define the location of the igniters 220 along the combustion tube 210. In the embodiment described herein, the igniters are located at the first and second full expansions along the path of inner swirl jets (253 a,b,c).

10   [0078] In a preferred embodiment, shown in Figures 3A-3E, the swirl plate 18 is a substantially circular disc having a thickness sufficient to fix the air flow pattern and to create an "air shroud" that is effective to protect the fuel injector. The thickness generally is about ½ inch or more. The swirl plate 18 has a central bore 255. The air assisted spray nozzle 16 is fitted to the swirl plate 18 at this central bore 255 using suitable means. In

15   the described embodiment, the swirl plate 18 has bores 240 therethrough for attachment of the air assisted spray nozzle 16. The swirl plate 18 is made of substantially any material capable of withstanding high temperature, a preferred material being stainless steel.

[0079] The central bore 255 is defined by a wall 244. Generally speaking, each type of

20   jet located at a given radial distance from the longitudinal axis of the swirl plate has four members (sometimes called a "set" of jets) spaced apart at approximately 90° along a concentric circle at a given distance from the central bore 255. Three sets of turbulent

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jets 248, 249, and 250 direct the air toward the central bore 255. The inner and outer sets

of swirl jets 242, 253, respectively, direct the air from the outer circumference 256 of the

swirl plate 18 and substantially parallel to a line 3C-3C or 4E-4E (Fig. 3C) through the

diameter the swirl plate in the respective quadrant in the direction of the burner.

5   [0080] The precise dimensions and angular orientation of the jets will vary depending

upon the inner diameter of the burner, which in the embodiment described herein is about

4 inches. Given the description herein, persons of ordinary skill in the art will be able to

adapt a swirl plate for use with a burner having different dimensions.

[0081] The orientation of the jets is described with respect to the front face of the swirl

10   plate 257, with respect to the longitudinal axis 241 of the swirl plate 18, and with respect

to the lines 3C-3C and 4E-4E in Fig. 3C, which divide the swirl plate 18 into four

quadrants. Six concentric circles 244 and 244 a-e (Fig 3C) are depicted, beginning at the

interior with the wall 244 defining the central bore 255 and extending concentrically to

the outer circumference 244e of the swirl plate 18. In the embodiment described herein,

15   the central bore has an inner diameter of 1.25 inches, or an inner radius of 0.625 inches.

A first concentric circle 244a is 0.0795 inches from the wall 244; a second concentric

circle 244b is 0.5625 inches from the wall 244; a third concentric circle 244c is 1.125

inches from the wall 244; a fourth concentric circle 244d is 1.3125 inches from the wall

244; and, a fifth concentric circle 244e is 1.4375 inches from the wall 244.

20   [0082] A set of outer swirl jets are labeled 242, and 242a,b,c. A set of inner swirl jets

are labeled 253 and 253 a,b,c. The outer swirl jets 242 and 242a-c and the inner swirl jets

253 and 253 a-c have the same angle z (Fig. 3B) relative to the surface 257 of the swirl

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plate 18, preferably an angle of 25°. In a preferred embodiment, both the outer swirl jets

242 and 242a-c and the inner swirl jets 253 and 253a-c have an inner diameter of 5/16."

The outer swirl jets 242 direct air from an entry point 242x along the outer circumference

256 of the swirl plate 18 on the fuel injection side 59 to an exit point 242y along circle

5   244b on the burner side 60. The longitudinal axis of the outer swirl jets 242 is parallel to

and spaced 0.44 inches from lines 3C-3C and 4E-4E in their respective quadrants. The

inner swirl jets 253 extend from an entry point along the circle 244b on the fuel injection

side 59 to an exit point on the burner side 60 along the central bore 244. The longitudinal

axis of the inner swirl jets 253 also is parallel to lines 3C-3C and 4E-4E in the respective

10   quadrants.

[0083] The air shroud jets 250 direct air from a point along the circle 244b directly

inward toward the center of the central bore 255. The longitudinal axis of the air shroud

jets 250 runs along the lines (3C-3C and 4E-4E). The angle a (Fig. 3D) of the

longitudinal axis 251 of the air shroud jets 250 with respect to the longitudinal axis 241

15   of the swirl plate 18 is 43.5°. The air shroud jets 250 preferably have an inner diameter of

about ¼ inch. The exit points 242y of the outer swirl jets 242 on the burner side 60 of the

swirl plate 18 preferably are aligned longitudinally, or in a direction parallel to the

longitudinal axis 241 of the swirl plate, with the entry points of the air shroud jets 250 on

the fuel injection side 59 of the swirl plate 18.

20   [0084] The air shroud jets 250 are primarily responsible for preventing the flame from

contacting the air assisted spray nozzle 16. The air flowing from the air shroud jets 250

converges at a location in front of the fuel injector 16 (Figs. 1 and 2) and creates a conical

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shroud of air which results in a low pressure area on the fuel injection side 59 (Fig. 1) of

the swirl plate 18 and a high pressure area on the burner side 60 of the swirl plate 18. The

low pressure area on the fuel injection side 59 helps to draw the fuel into the combustion

tube 210 while the high pressure area on the burner side 60 prevents the burner flame

5   from attaching to the face of the air assisted spray nozzle 16, and prevents coking and

overheating of the nozzle 16. In a preferred embodiment, the air shroud jets 250

converge from about 0.5 cm to about 1 cm in front of the nozzle 16.

[0085] The combustion tube 210 is equipped with several spark igniters 220 (see Figure

2). In a preferred embodiment, three substantially equally spaced igniters 220 are located

10 around the circumference of the combustion tube in the gas "swirl path" created by the

swirl plate 18. In a preferred embodiment these igniters 220 are marine spark plugs.

[0086] In an alternate embodiment, suitable for combustion of low volatility fuels, the

combustion tube 210 is further equipped with ceramic foam located about one foot

downstream from the spray nozzle 16. Substantially any suitable foam may be used,

15 preferably 10 pore/inch SiC ceramic foam commercially available, for example, from

Ultra-Met Corporation, Pacoima, CA 91331.

-Interaction of fuel injector and swirl plate

[0087] The burner 60 and the fuel injector 16 work together to provide substantially

continuous and "effective stoichiometric combustion." As used herein, the term

20 "effective stoichiometric combustion" refers to stoichiometric combustion which

maintains the integrity of the wall of the combustion tube without substantial coking of

the fuel injector. As a result, the burner may run substantially continuously at

stoichiometric for at least 200 hours without the need for maintainence. In a preferred embodiment, the burner may run substantially continuously at stoichiometric for at least 1500 hours with minimal maintenance. By minimal maintenance is meant spark plug changes only.

[0088] The design of the fuel injector 16 (above) takes into account the primary features of the swirl plate 18, namely:

1)   The outer turbulent jets 248 and 249 (shown in Section 3C-3C) keep the flame from remaining in constant contact with the interior wall of the combuster tube 210. Because the burner 60 operates continuously, and for extended times at stoichiometric (the hottest air/fuel ratio operating point), it is necessary to maintain the integrity of the wall of the combustion tube 210. Currently, the INCONEL combustion tube 210 has been exposed to over 1500 hours of operation, without showing evidence of deterioration. This feature does not substantially affect fuel injection.

(2)   The inner swirl jets 242 set-up the overall swirl pattern in the burner. Air exiting the inner swirl jets 242 impacts the interior wall of the combuster tube 210 about 3 inches downstream of the swirl plate 18, and directly interacts with the spray of fuel from the fuel injector 16.

(3)   The inner turbulent jets 250, are sometimes referred to as the 'air shroud' jets. Air exiting the inner turbulent jets 250 converges 0.75 inches in front of the fuel injector 16. This feature provides two very important functions. The point of convergence creates a high pressure point in the burner 60, which prevents the burner flame from

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attaching to the fuel injector 16 (preventing coking). The second function, which

interacts directly with fuel injection and impacts flame quality, is that it shears the

remaining large fuel droplets as they enter the burner flame.

The Heat Exchanger

5   [0089] The exhaust from the burner 60 is routed to a heat exchanger 70. The heat

exchanger 70 may be of any conventional design which will be well known to a person of

ordinary skill in the art. In a preferred embodiment the heat exchanger 70 consists of two

sections. The upstream section consists of a water jacketed tube. The downstream

section is a vertical cross flow shell and tube heat exchanger. The vertical cross flow

10   design minimizes steam formation and steam trapping within the cooling tubes. The heat

exchanger 70 is provided with an inlet water line 80 and an outlet water line 90 which

supply and drain cooling water to cool the exhaust gas to a temperature simulating that

which is present at the inlet to the catalytic converter of a typical motor vehicle.

[0090] Referring now to Figure 4 which shows details of the heat exchanger of the

15   preferred embodiment, for the upstream section, a shell 305 is fitted with a water inlet

connection 306. The shell 305 functions as a water jacket for an inner tube which

contains the exhaust gases from the burner. Water flows through the water jacket which

is fitted with several baffles 308 to direct the water around all parts of inner tube. At the

downstream end, the shell 305 is fitted with an outlet water connection 309.

20   [0091] For the downstream section of the heat exchanger, a shell 310 is fitted with a

water inlet connection 320 which is in turn connected to an inlet header 330. The inlet

header 330 is in fluid communication with a plurality of one half inch tubes 340 which

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extend from the bottom to the top of the shell 310 whereupon the plurality of one half

inch tubes 340 are in placed in fluid communication with an outlet header 350 which is

fitted with an outlet water outlet connection 360. In operation hot exhaust gas is directed

through the shell 310 where the gas comes in contact with the plurality of one half inch

5   tubes 340. Cooling water is circulated into the inlet water inlet connection 320

whereupon it is directed by the inlet header 330 to flow through the plurality of one half

inch tubes 340. Heat which is present in the exhaust gas is conducted into the cooling

water, producing an exhaust gas of a reduced temperature at the outlet of the heat

exchanger 70 of Figure 1.

10   **The Oil Injection System**

[0092] The exhaust gas is next routed to an oil injection section 110 (Fig. 1). The oil

injection section provides an atomized oil spray comprising oil droplets with a

sufficiently small diameter to vaporize and oxidize the oil before it reaches the catalyst.

The oil injection system may be located anywhere downstream from the burner.

15   [0093] A series of test runs were conducted using a Malvern laser particle sizing

instrument to determine the preferred oil droplet size as a function of nitrogen pressure in

the gas assist line. Suitable oil droplet sizes have a Sauter mean diameter of less than 80

microns, most preferably a Sauter mean diameter of about 20 microns or less.

[0094] In operation, a sample of motor oil is withdrawn from an oil reservoir 150 (Fig.

20   1) by means of an oil pump 160. Substantially any type of pump may be used, preferably

a peristaltic pump which feeds the oil from the reservoir through an oil injection line 140

and into a water cooled probe 120 from which the oil is injected into the exhaust gas

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which is present in the oil injection section 110.

[0095] The oil injection system is installed in a four inch diameter pipe, and placed in a location where the exhaust gas temperature is approximately 600 °C. In a preferred embodiment, the oil injection section 110 is constructed as depicted on Figures 6A and

5   6B. In this embodiment, a separate oil injection line 434 and nitrogen injection line 410 pass through a coupling 430 which is threaded into the injection section housing 432 and into a water cooled sleeve 420 in the injection section housing 432. The oil injection line 434 communicates with the machined oil ring 444 (Fig. 6A) of the oil injection nozzle 440. The nitrogen injection line 410 communicate with the machined air ring 448 (Fig.

10   6A) of the oil injection nozzle 440. In addition to the machined oil ring 44 and the machined air ring 448, the oil injection nozzle comprises a modified bolt 442, an o-ring seal 446, a stock jet 450, and a stock nozzle 452.

[0096] In operation, a coolant solution, preferably water, is continuously circulated through the sleeve 420, which jackets the oil injection line 434 and nitrogen injection line

15   410, causing the oil and nitrogen injector system to remain at the desired temperature. Lubricating oil is pumped via the oil injection line 434 into the nozzle 440, where the oil is mixed with the nitrogen. The resulting nitrogen/oil mixture is injected into the exhaust gas through the nozzle 440. The exhaust gas having been mixed with the injected oil is finally passed through an automotive catalytic converter 170 following which the exhaust

20   gas is vented to the atmosphere via an exhaust line 180.

The Computerized Control System

[0097] Referring now to Figure 7, there is provided a data acquisition and control system

25

suitable for use with the present application. The system preferably provides a means to

control ignition, air assist to the fuel injector, auxiliary air, fuel feed, blower air feed, oil

injection, etc. (discussed more fully below). An example of a suitable control system

would be a proportional integral derivative (PID) control loop, for example, for

5   controlling fuel metering.

[0098] The data acquisition system comprises a series of test probes 610, 620, 630 which

collect data regarding a number of parameters. Suitable parameters are selected from the

group consisting of: the mass air flow in the system; the air/fuel ratio (linear and EGO);

the exhaust gas temperature at the outlet from the heat exchanger; the exhaust gas

10   temperature at the inlet to the catalyst; the exhaust gas temperature at the outlet from the

catalyst; and, a combinations thereof. In a preferred embodiment, data is collected for all

of the foregoing parameters. The information measured by the test probes is transmitted

by electronic signals to an electronic data recording system 650. In a preferred

embodiment the electronic data recording system comprises a computer system with a

15   program which causes the computer to measure all of the monitored parameters on a

periodic basis, to record all of the data obtained on a hard drive.

[0099] Preferably, the data acquisition and control system monitors the test stand for

safety (for example by verifying that the burner is lighted and that the exhaust is within

specified limits for both temperature and air to fuel ratio). The control system contains an

20   auto start and auto shutdown option. After the burner fuel is activated, a set of safety

checks automatically initialize and monitor the burner for malfunction. While a test is in

progress the program collects data at 4 Hz, stores data at 0.5 Hz and displays the catalyst

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inlet, bed, and outlet temperatures and measured air to fuel ratio at 1 Hz, allowing the

operator to review the overall stability of the system. Operating a gasoline fuel burner

unattended for long periods of time is potentially dangerous. The system uses three built-

in safety limits to check for system malfunction. The heat exchanger outlet must reach a

5   temperature greater than 100 °C within four seconds after activation of fuel injection and

maintain a minimum safety setpoint level during operation, indicating that the burner is

properly ignited and remains lit. The third setpoint checks the catalyst bed temperature to

verify that the catalyst is not at a temperature that could be detrimental to the experiment.

If any of the safety setpoints are compromised, the computer is programmed to turn off

10   all test systems, divert the blower flow, activate a two minute nitrogen purge into the

burner head to extinguish the burner flame and suspend any unburned fuel in nitrogen,

thereby preventing a large exothermic reaction in the test apparatus. A bright red screen

is displayed describing the condition at which the system was shut down, along with the

date and time. Data are continuously recorded at 4 Hz for ten minutes after a safety

15   compromise. In addition, the nitrogen purge system is also activated and a safety

shutdown is followed when an electrical power loss is detected.

[00100] In a preferred embodiment the data acquisition and control system is also capable

of controlling a number of parameters, including controlling the lube oil injection and

burner systems. The computer is equipped with a touch screen monitor and a multi-

20   function DAQ card, connected to an digital relay module to monitor and record system

information, and to control system electronics. Using the computer interface, the operator

can switch power to the blowers and fuel pump, as well as control the air assisted fuel

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injectors, burner spark, oil injection, and auxiliary air, all with the touch of the screen.

System temperatures, mass air flow for the burner air, and the burner air to fuel ratio are

measured and converted to engineering units. The software program uses measured data

to calculate total exhaust flow and burner air to fuel ratio, and to check conditions

5   indicative of a system malfunction. The burner air to fuel ratio may be controlled as

either open or closed loop, maintaining either specified fuel flow or specified air to fuel

ratio. Air to fuel ratio control is achieved by varying the rate of fuel delivered to the

burner (modifying the pulse duty cycle of a fixed frequency control waveform).

Whenever necessary, open loop control can be activated allowing the operator to enter a

10   fixed fuel injector pulse duty cycle. Closed loop control can be activated in which the

actual burner air to fuel ratio is measured and compared to the measured value of the air

to fuel setpoint and then adjusting the fuel injector duty cycle to correct for the measured

error. The front panel of the program is used to allow the user to input an aging cycle,

and to run the test using a single screen.

15   [00101] In a preferred embodiment, the data acquisition and control system is provided

with a computer program to control the system and to acquire and process the signals

from the measured parameters. The computer program can be written in a variety of

different ways, which will be well known to persons versed in the art. The controller

preferably is provided with a closed-loop fan control to maintain catalyst inlet

20   temperature, preferably at from about -50 °C to about +50 °C about a setpoint

temperature, preferably from about -5 °C to about +5 °C about a setpoint tempererature.

The setpoint temperature is dictated by the cycle being simulated. Figure 10 shows a

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schematic of a suitable closed-loop fan control in which the controller output varies the

speed of the cooling fans from off, to low, to high.

[00102] The application will be better understood with reference to the following

working examples, which are illustrative only.

5   **Example 1**

[00103] A series of tests was performed to determine the droplet sizes for lubricant

injected into the system. Results of droplet sizing tests are shown in Figure 8. The figure

shows the "Sauter mean diameter" of the droplets in microns (labeled "D(3,2)") as a

function of air pressure for the planned oil flow of 0.8 mL/min. The Sauter mean

10   diameter (or SMD or D_{32}) is the drop diameter of an idealized monodisperse spray that

has the same surface area-to-volume ratio as the actual polydisperse spray. The surface

area-to-volume ratio correlates with the evaporation rate of the spray, so the SMD is a

common measure of spray characteristics for evaporating or combusting sprays. The

SMD is defined mathematically as:

15
$$SMD = D_{32} = \frac{\sum n_i D_i^3}{\sum n_i D_i^2}$$

20
where n_i is the number of drops in size class D_i. From the figure, it can be seen that the

droplet size decreases with increasing air pressure. If there were no other considerations,

the highest pressure would be used to give the smallest droplet, since it is desirable to

have as much of the oil evaporate as possible. For this apparatus, however, nitrogen, not

air, was used for the "air assist" gas. The nitrogen consumption preferably is kept at a minimum, both from an operating cost standpoint, and to keep the percentage of nitrogen in the exhaust stream as low as possible. As a result, there is a trade-off between the droplet size and pressure. Acceptable pressures were determined during the optimization testing of the apparatus.

[00104] To assist in determining the pressure-droplet size tradeoff, a computer simulation was run using a computer program (TESS, Southwest Research Institute) that calculates the amount of the liquid which will evaporate at various locations downstream of the liquid droplet injection. The computer simulation assumed a 2.5 inch diameter pipe and exhaust gas flow of 50 scfm at 400 °C. The oil spray had an SMD of 20 microns. The spray half-angle with respect to the center line was 9 degrees.

[00105] Figure 8 shows the droplet trajectories for various size droplets in a droplet distribution with an SMD of 20 microns. The larger droplets hit the wall of the 2.5 inch diameter pipe (31.75 mm radius) at approximately 250 mm downstream from the nozzle. With a 20 micron SMD, about 75 percent of the oil evaporates, and 25 percent impinges on the wall. With a 30 micron SMD, only 50 percent of the oil evaporates before impinging on the wall. Based on this data, it is important to have the SMD as small as possible.

Example 2

[00106] A series of tests were performed in order to demonstrate that the apparatus could provide useful information on full scale catalytic converter durability with oil injection. The tests were performed with catalyst bricks identified in the following Table:

Catalyst Manufacturer	Englehard
Designation	FEX-010-M2
Size	3.268" Dia. by 3.0" Long
Cell Density	400 cells/sq. in.
Catalytic Metals	Palladium/rhodium @9:1
Metal Loading	60 g/cu. ft.

[00107] Fully formulated lubricant oils were used for the tests, by which is meant that the lubricant oils had detergents and other additives as well as base lube stock. The lubricant oils are described in the following table:

	Oil No. 1	Oil No. 2
SwRI identification	EM-2209-EO	EM-2210-EO
SAE viscosity	5W30	5W30
density, g/cu. Cm	0.867	0.865
Weight Percent Phosphorus	0.11	0.06

[00108] Modern computer controlled vehicle engines provide two modes of fuel control, an open-loop control (engine crank, warm up, hard acceleration), and stoichiometric closed-loop control (part throttle and idle conditions) after the catalyst has reached operating temperature. During the closed-loop mode the engine air-fuel ratio is constantly perturbating between slightly rich and slightly lean (due to the on-off switch type operation of the exhaust oxygen sensor used for feedback). Performance evaluation tests were therefore conducted using simulations of the rich open-loop (steady state) mode and the perturbated stoichiometric closed-loop mode. The temperature at which the HC, CO and NOx conversion efficiency reached 50 percent was evaluated during the rich steady-state air-fuel ratio tests, and the catalyst HC, CO, and NOx efficiency at 425 °C

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was evaluated during perturbated stoichiometric tests.

[00109] The results of the light-off and steady state efficiency evaluations are presented in the table below. The data are presented in ascending order of amount of oil injected, rather than in chronological order in which the catalyst was aged or evaluated.

Validation Test Results

Core	Location inches	Hours	Oil Used, mL	Oil, mL/hr	P, wt%	Total P, grams	P, mg/hr	Rich Steady-State Temp. °C at 50% Conversion			Perturbated Stoichiometric % Conversion @ 425 °C		
								HC	CO	NO_x	HC	CO	NO_x
REF	N.A.	0	0	0	0	0	0				71	96	50
B4	30	25	500	20	0.11	0.476	19.05	374	310	314	88	98	52
B5	30	25	500	20	0.06	0.260	10.39	377	312	335	88	99	47
B4(avg, of 2)	30	50	1000	20	0.11	0.953	19.05	372	313	329	84	95	44
B5(avg. of 2)	30	50	1000	20	0.06	0.520	10.39	374	319	341	86	93	53
B1	56	37.5	3781	100.8	0.11	3.602	96.05	382	320	330	79	88	44

[00110] The catalyst conversion efficiencies for HC, CO, and NOx from the perturbated stoichiometric tests as a function of oil injected were determined. For HC and CO, there was about a 10 percentage point decrease in conversion efficiency between the smallest amount of oil injected and the largest amount. For NOx, there was approximately a 5 percentage point decrease over the same oil injection range. Note that while there were sometimes differences in conversion efficiency between the 0.11 weight percent phosphorus oil and the 0.06 weight percent phosphorus oil, there was no clear correlation with the percent phosphorus.

[00111] The temperature at which 50 percent conversion efficiency was obtained during rich light-off as a function of oil injected was determined. As can be seen from the table

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of validation test results above there was a slight increase in the 50 percent conversion

efficiency temperature for HC, CO, and NOx, indicating a slight deterioration in the

ability of the catalyst to light-off. This temperature increase was small, however. As was

seen with the efficiency measurements, there did not appear to be a measurable difference

5   in light-off temperature between 0.11 and 0.06 percent phosphorus oil.

[00112] It is generally assumed by those skilled in the art that it is the phosphorus in the

oil which poisons the catalytic converter catalyst. Thus, for equal volumes of oil injected,

one would expect that oil with a higher phosphorus level would poison the catalyst to a

greater extent. This trend was not clearly evident from the validation test results

10   presented above. The question thus arises as to whether there is really no difference in

catalyst performance with varying phosphorus levels, at least over the range tested, or

whether the present application was unable to replicate a difference that might be seen in

actual engine operation. In order to explore the catalyst performance differences more

fully, the amount of phosphorus injected during each test was calculated from the weight

15   percent phosphorus, the oil density, and the volume of oil injected. The total amount of

oil and phosphorus injected, and the oil and phosphorus injection rate for each test, are

also presented in table of validation test results above.

[00113] The perturbated conversion efficiencies for HC, CO and NOx, respectively, as a

function of total phosphorus mass injected were determined. Comparing the conversion

20   efficiencies for all emissions as a function of phosphorus mass and as a function of oil

injected, it appears that the plots against phosphorus mass show slightly less data spread

than was seen in the plots of oil consumed. This observation lends credence to the

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assumption that it is the phosphorus in the oil that poisons the catalyst. The 50 percent

conversion temperature for the rich light-off tests as a function of total phosphorus mass

were determined. Less data spread was seen than in previous examples.

Example 3

5   [00114] Testing was done to compare the exhaust gas of a typical gasoline fueled engine

to the burner system of the present application. Figure 9 shows measured, raw exhaust

gas concentrations for the present system (50 SCFM) and a Ford 4.6L, V-8 engine (50

SCFM, 1500 rpm, 90 lb-ft, no EGR), both operating on the same batch of CA Phase II

fuel, at a slightly lean and a slightly rich exhaust A/F. The A/F was calculated using the

10   measured raw exhaust gas composition and fuel properties; a method well known to those

versed in the art.

[00115] Fig. 9 shows that the exhaust of the present system contains much lower THC

and NO_x levels, compared to a Ford 4.6L engine. The CO level is about half to three

quarters of the engine level, and the CO_2 and O_2 are approximately the same (as these two

15   elements are largely controlled by AFR, not combustion conditions). THC is low because

the burner is highly efficient with steady, well vaporized fuel flow, and there are no

quench regions resulting in partial burn, as in an engine. NO_x is low because the burner

operates at near atmospheric pressure, unlike an engine in which NO_x is a result of the

high pressure of combustion. Nevertheless, the exhaust gas of the present system can be

20   considered sufficiently similar to engine exhaust gas because the exhaust gas is

considered simply a "carrier gas" for the potential catalyst poisons.

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Example 4

[00116] In order to compare the results produced by the instant application with those

which would be obtained with an actual internal combustion engine, the results were

compared to those provided in Beck, D.C., Somers, J.W., and DiMaggio, C.L., "Axial

5   Characterization of Catalytic Activity in Close-Coupled Lightoff and Underfloor

Catalytic Converters", Applied Catalysis B: Environmental, Col. 11 (1977) pages 257-

272, Elsevier Science B.V. ("Beck"). The Beck vehicle had a 3.8 liter V-6 engine with

close coupled "light-off" catalytic converters in the exhaust from each cylinder bank of

the engine, and the outlets from these were combined into a single pipe containing a

10   single underfloor converter. The light-off catalyst contained only palladium at a loading

of 75 g/cu.ft. This catalyst was similar to the catalyst used in the testing of the instant

application, as described in the first table of Example 2.

[00117] Phosphorus tends to collect more at the upstream end of the catalyst. In Beck,

the three inch long light-off catalysts were cut into three sections, each one inch thick,

15   starting at the upstream face. As expected, the phosphorus contained in each section

decreased with distance from the front face. A phosphorus analysis of each section

showed that the upstream section contained 1.6 weight percent phosphorus, the middle

section 0.9 percent, and the downstream section 0.25 percent phosphorus. The samples

from the Beck catalysts were tested for conversion efficiency in a synthetic gas reactor

20   system, similar to that employed to determine the conversion efficiencies of the instant

application. Warmed-up performance of these samples was tested at stoichiometric air-

fuel ratio and 600 °C for HC, CO, and NOx respectively. Beck presents conversion

efficiencies from three samples with three different levels of phosphorus poisoning, comparable to the validation tests of the instant application with various levels of phosphorus. Furthermore, Beck states that "The absolute concentrations of phosphorus and zinc are consistent with those found in .. other... converter systems which have been

5   extensively aged," suggesting that the vehicle used in this study consumed oil at a relatively nominal rate. This nominal exposure for 56,000 miles is also comparable to the maximum validation test of the instant application of 100mL/hr for 37.5 hours, which is equivalent to roughly 37,500 miles of nominal exposure. Thus, it appears that the conversion efficiency results of the instant application can be quantitatively compared to

10 the conversion efficiency results of the Beck study, assuming the maximum phosphorus rates in that study and the validation tests of the instant application both represent nominal oil consumption for approximately 50,000 miles.

[00118] Comparing the conversion efficiencies of HC, CO and NOx with increasing phosphorus from the two studies, there is about a 10 percent drop in HC efficiency over

15 the data range for both sets of data. For CO efficiency, the drop is less than 10 percentage points for both sets of data. For NOx efficiency, the overall trend of decreasing efficiency with increasing phosphorus is the same for both data sets, but the data set from the Beck study has a slightly greater decrease than the data of the instant application. The data derived from the instant application also show a lower NOx efficiency than the Beck data.

20 Overall, the data sets look remarkably similar, thus demonstrating that the instant application can produce phosphorus poisoning data similar to that seen in the field.

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Example 5

[00119] The objective of this work was to develop a control method for the FOCAS™ burner system (adding subsystems if necessary) that would allow the burner to simulate exhaust temperature, flow, and AFR created by an engine during accelerated thermal

5   aging. Next, the methodology was validated by determining if the burner system provides accelerated thermal aging comparable to an engine. The validation portion of the study examined the aging differences between six like catalysts, aged using the General Motors Rapid Aging Test version A (RAT-A) cycle. Three catalysts were aged using a gasoline-fueled engine, and the other three used the modified FOCAS™ burner system. Both

10   systems were programmed to run to the engine test cycle specifications to provide identical inlet temperature, AFR profiles, and catalyst space velocity conditions. The catalyst performance at defined intervals and at the conclusion of the aging was measured and compared between the two systems. In addition, the variation and repeatability of the temperature and AFR control of each system were assessed and compared.

15   [00120] One industry-accepted engine-based catalyst accelerated aging cycle which was used as a reference point in this study is the General Motors Rapid Aging Test Version A (RAT-A) cycle. A simulation of the RAT-A cycle was run on the FOCAS™ burner system and compared to the cycle run on the engine. It was demonstrated that the burner can be used to generate a very similar thermal profile inside the catalyst when compared

20   to the profile generated by the engine. The shape of the thermal excursion was reproduced, and the AFR into the catalyst could be controlled and reproduced. Two differences were noted between the two systems; there appeared to be some burning of

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the reactants in the exhaust pipe, prior to entering the catalyst in the burner system, and

the FOCAS™ burner had much tighter AFR control than the engine. The burning of the

reactants before the catalyst resulted in a slight shift forward of the location of the peak

temperature during the thermal excursion. The thermal profiles generated by the engine

5   and by the burner are shown in Fig. 11, along with the measured AFR for each system.

[00121] The similarity was then tested by using the FOCAS™ burner system to age

catalysts. During the testing portion of the program, six catalysts were aged for 100 hours

on the RAT-A cycle; three on an engine aging stand, and three on the FOCAS™ burner

system. The catalyst performance at defined intervals and at the conclusion of the aging

10   was measured and compared between the two systems. In addition, the variation and

repeatability of the temperature and AFR control of each system were assessed and

compared.

[00122] The performance evaluations consisted of comparing the regulated emissions

across the Federal Test Procedure (FTP) and using an engine-based catalyst performance

15   evaluation rig to measure the catalyst conversion efficiency as a function of exhaust

air/fuel ratio (AFR) and catalyst light-off temperature. FTP emissions utilized a 1998

Honda Accord vehicle, while engine-based catalyst performance evaluations were

performed on an engine stand.

[00123] The FTP performance evaluations showed that the burner and the engine

20   produced equivalent aging effects, resulting in deterioration factors for THC, CO, and

NOx that were not statistically different between the two methodologies. Figure 12

shows the average FTP performance for the engine- and burner-aged catalysts, before and

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after aging. The engine- based catalyst performance evaluations revealed that the two

methodologies produced equivalent results near stoichiometric (where a gasoline engine

is tuned to run). However, as the AFR deviated from stoichiometric to the rich side it

was observed that burner aging resulted in a more severe aging effect for THC and CO

5   (slight at AFR >14.1, more severe at AFR <14.05). Although the difference in this effect

was small and shifted from the location of typical operation, it was noted as a difference.

Fig. 13 shows the measured THC conversion efficiency as a function of AFR and catalyst

age.

[00124] The final catalyst evaluations involved coring the catalysts, and analyzing the

10   surface area and composition. The two analyses run were BET (Bruhauer-Emmett-

Teller) for assessment of surface area and porosity, and PIXE (Proton-Induced X-Ray

Emissions) for compositional analysis. The BET test provides information on the surface

area of the substrate and washcoat. This analysis can be correlated to thermal

degradation. PIXE provides information on the composition of the substrate, washcoat,

15   and any deposits on the surface of the catalyst. PIXE analysis can provide information on

the differences in the deposits on the catalysts between the engine and the burner (which

provides oil-free aging). It was found that the catalysts were composed of very similar

levels of washcoat, but that the FOCAS™ aged catalysts had an obvious absence of oil-

derived deposits. However, the levels of oil deposits found on the engine-aged catalysts

20   were small, and it is likely that they did not impact performance.

[00125] Overall, it was found that the FOCAS™ burner system provided a flexible

means for simulating the engine aging cycle, and produced thermal aging results

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equivalent to the engine cycle. The post-mortem analysis shows that the FOCAS^{TM} aging

provides thermal aging in the absence of non-thermal aging (i.e. oil deposits), thereby

creating a means for the definitive isolation of thermal and non-thermal aging effects.

Some advantages that using a burner offers over an engine for aging include: very tight

5   AFR control (±0.02 AFR), very broad range of stable AFR operation (8:1 to 25:1), few

moving parts (a blower and a fuel metering valve), and minimal adjustments to achieve

setpoints. Also, a burner can be run at very high temperatures without severely damaging

the system components, making for a low cost, low risk simulation of very-high-

temperature cycles.

10   **Example 6**

[00126] Seven general design criteria/guidelines were used to design preferred fuel

injector. These criteria were:

1)   Pressure in the air channel could not exceed pressure in the fuel channel or fuel flow

would be interrupted. Assuming the burner flow is steady-state (a reasonable

15   assumption):

$$For\ Air:\ \frac{P_{1_A}}{A_{1_A}} \times A_{2_A} = P_{2_A} \qquad For\ Fuel:\ \frac{P_{1_f}}{A_{1_f}} \times A_{2_f} = P_{2_f}$$

2)   Desired fuel inlet pressure (based on fuel pump specifications) is 40 psig $< P_f <$ 60

psig.

3)   The area of the fuel jets must provide adequate fuel flow for the required flow range,

20   in the given operating pressure range.

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4) The size of the fuel holes must be a standard drill bit size, and must be large enough to allow machining without excessive difficulty.

5) Fuel/Air spray should aim for outer air shroud convergence to keep the burner flame off the combustor wall as long as possible.

6) Direct point of fuel jet convergence behind air shroud. Adjustment of P_A can be used to vary the position of the fuel spray relative to the air shroud.

7) Keep interaction point of the fuel and the air jet at the center of the combined outlet hole to prevent driving the fuel spray to the inner wall of the injector. This would lead to dripping, and coking of the face of the injector.

8) The degree of atomization and stability was determined visually, using the quartz combustor. The assessment was based on the blueness of the flame (orange flames indicated sooty conditions), the soot forming potential (assessed by examining the injector, combustor, heat exchanger and exhaust pipe), and the stability of the flame (assessed using a linear AFR sensor).

Since the burner is designed to operate predominantly at stoichiometric, the required fuel flow was calculated using the required total exhaust gas flow and the stoichiometric AFR of the fuel used for aging. The following analysis presents the calculation of the required fuel flow for the burner operating at stoichiometric, with a total exhaust flow of 70 SCFM.

$$m_{exh} = 70 \text{ SCFM} = 2.3015 \text{ kg/min}$$

$$m_{fuel} = m_{exh} \times AFR_{stoich}^{-1} \times 1 \text{ lb/0.45359 kg} \times 60 \text{min/hr}$$

$$m_{fuel} = 21.28 \text{ lb/hr at stoichiometric}$$

$$m_{air} = m_{fuel} \times (AFR_{avg} / AFR_{stoich})$$

$$AFR_{avg} = (16/60 \times 13) + (44/60 \times 14.4) = 14.03 \quad \text{RAT-A cycle}$$

$$m_{air} = 65.1 \text{ SCFM}$$

Therefore, the rate of energy consumption of the burner over the cycle is:

$$Q = m_{fuel} \times \text{Energy content of fuel}$$
$$Q = m_{fuel} \times 18,400 \text{ BTU/lb} = 21.28 \text{ lb/hr} \times \text{hr/3600sec} \times 18,400 \text{ BTU/lb} \times 1.055 \text{ KJ/BTU}$$
$$Q = 115 \text{ kW}$$

[00127] Referring to Figure 20, the distance l_1 is the radius of the combustor tube, and l_2 is the distance to impact with the inner wall of the combustion tube 210. The distance l_2 can be calculated using geometry, but then is corrected for interaction with the fuel jet (which tends to lengthen l_2) and the inner swirl jets 242 (which tend to shorten l_2). The inner swirl jets 242 have the greatest impact. The final angle for X,X' is a function of fuel shearing and atomization (which is improved with lower X,X') and preventing impact with the wall of the combustion tube 210 by directing the fuel spray into the area where the outer swirl jets 253 in Fig. 3 converge (about four to five inches from the face of the swirl plate). These outer swirl jets 253 help to keep the hottest part of the flame off the inner wall of the combustion tube 210, which enables the burner to run stoichiometric for extended periods of time. Table 1 shows calculated impact of the fuel spray with the wall of the combustion tube 210, with and without swirl jet interaction. From these data, two fuel injectors were built, E-62 and E-76 (where the number refers to the angle X,X' in degrees).

Table 1

Air Injection Angle, X,X'	Calc. Impact Distance, No Interaction, in.	Observed Impact, in.	Calc. Impact Distance with Medium Interaction, in.
60	2.75		2.5
61	2.88		2.57
62	3.03		2.64
63	3.18		2.71
64	3.34		2.8
65	3.52		2.89
66	3.71		2.98
67	3.92		3.08
68	4.14	3.25 - 3.5	3.2
69	4.38		3.32
70	4.65		3.45
71	4.95		3.6
72	5.27		3.76
73	5.63		3.94
74	6.04		4.14
75	6.5		4.37
76	7.02		4.64
77	7.62		4.94
78	8.32	5	5.29
79	9.15		5.7
80	10.13		6.19

5

[00128] Experiments were performed to develop a control method for the FOCAS™ burner system (adding subsystems if necessary) that would allow the burner to simulate exhaust temperature, flow, and AFR created by an engine during accelerated thermal aging. The methodology was validated by determining if the burner system provided

10   accelerated thermal aging comparable to an engine. The validation portion of the study examined the aging differences between six like catalysts, aged using the General Motors Rapid Aging Test version A (RAT-A) cycle. Three catalysts were aged using a gasoline-

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fueled engine, and the other three used the modified FOCAS™ burner system. Both

systems were programmed to run to the engine test cycle specifications to provide

identical inlet temperature, AFR profiles, and catalyst space velocity conditions. The

catalyst performance at defined intervals and at the conclusion of the aging was measured

5   and compared between the two systems. In addition, the variation and repeatability of the

temperature and AFR control of each system were assessed and compared.

[00129] The baseline performance of the systems was tested using a engine-based

catalyst performance evaluation rig. Catalyst performance is measured as a function of

exhaust air/fuel ratio and exhaust gas temperature. The catalysts were degreened by

10   operating for four hours on the RAT-A engine aging cycle. Each catalyst's performance

was then reevaluated. Each system was then installed on the vehicle and two Federal Test

Procedures (FTP) evaluations were performed. The FTP is a chassis-based vehicle

emissions test cycle, used for certifying vehicle emissions and fuel economy. The

emissions from the FTP cycle are regulated by EPA according to vehicle type. Six

15   catalysts with closest performance were selected and randomly assigned to be engine or

burner aged. The seventh catalyst was the 'set-up' catalyst.

TEST EQUIPMENT AND PROCEDURES

20   [00130] A certification grade California Phase II gasoline obtained from Phillips 66 was

used as the test fuel throughout all vehicle testing. The following Table gives the supplier

analysis of this fuel.

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Item	Specification		Supplier Analyses
	ASTM	Unleaded	
Octane, research	D2699	93 (min.)	97.7
Sensitivity		7.5 (min.)	10.3
Pb (organic), g/U.S. gal	D3237	0.050	NR

Distillation Range:
  IBP °F
  10% Point, °F
  50% Point, °F
  90% Point, °F
  EP, °F
	D86
	D86
	D86
	D86
	D86
		75-95
		130-150
		200-230
		290-310
		390 (max.)
			104
			143
			206
			292
			375

Sulfur, wt. %	D1266	0.10 (max.)	31
Phosphorus, g/U.S. gal.	D3231	0.005 (max.)	0.001
RVP, psi	D323	6.7-7.0	6.8

Hydrocarbon Composition:
  Aromatics, %
  Olefins, %
  Saturates, %
	D1319
	D1319
	D1319
		23-25 (max.)
		4-6 (max.)
		a
			23.5
			5.95
			---- 	

[a] Remainder NR - Not reported			

A pump grade California Phase II gasoline was used for aging and performance evaluations.

The difference between the two fuels was that the pump grade had detergents that prevented

engine deposits.

A.   Chassis Dynamometer Testing

[00131] All emissions tests were conducted in accordance with the EPA Federal Test

Procedure (FTP), which utilizes the Urban Dynamometer Driving Schedule (UDDS).

The UDDS is the result of more than ten years of effort by various groups to translate the

Los Angeles smog-producing driving conditions to chassis dynamometer operations, and

is a nonrepetitive driving cycle covering 7.5 miles in 1372 seconds with an average speed

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of 19.7 mph. Its maximum speed is 56.7 mph.

[00132] An FTP consisted of a cold-start, 505-second, cold transient phase (Bag 1),

followed immediately by an 867-second stabilized phase (Bag 2). Following the

stabilized phase, the vehicle was allowed to soak for 10 minutes with the engine turned

off before proceeding with a hot-start, 505-second, hot transient phase (Bag 3) to

complete the test. For a 3-bag FTP, the distance traveled was 11.1 miles at an average

speed of 21.6 mph. The vehicle's exhaust was collected, diluted, and thoroughly mixed

with filtered background air to a known constant volume flowrate using a positive

displacement pump. This procedure is known as Constant Volume Sampling (CVS). A

proportional sample of the dilute exhaust was collected in a sample bag for analysis at the

end of the test. The emissions were mathematically weighted to represent the average of

several 7.5 mile trips made from cold and hot starts. A speed versus time illustration of

the 505 and 867 phases of the FTP driving cycle is given in Fig. 14. A summary of cycle

duration, driving distance, and average speed is given in the following Table:

Segment	Duration, seconds	Distance, miles	Average Speed, mph
Transient Phase	505	3.60	25.7
Stabilized Phase	867	3.90	16.2
UDDS Total	1372	7.50	19.7
(FTP CYCLE IS UDDS + HOT-START TRANSIENT 505)			

Exhaust emissions from the FTP cover the effects of vehicle and emission control system

warm-up as the vehicle is operated over the cycle. The "stabilized" phase produces

emissions from a fully warmed up or stabilized vehicle and emission control system. "Hot-start" or "hot transient" phase emissions result when the vehicle is started after the vehicle and emission control systems have stabilized during operation, and are then soaked (turned off) for 10 minutes.

5   [00133] Weighted total emissions from the FTP at 68°F to 86°F ambient temperature conditions are regulated by the EPA. The only regulated pollutant for the FTP at cold conditions (20°F) is carbon monoxide (CO). Tier 1 cold-CO level for passenger cars is 10.0 g/mile. The California ULEV emissions standards for 1998 light-duty passenger cars, intermediate life - 50,000 miles (the standards which the test vehicle was certified

10   to) are:

NMOG: 0.04 g/mile
CO: 1.7 g/mile
NO_x: 0.2 g/mile

15
The weighted total mass equivalent emissions for the EPA FTP-75 are calculated as required in the U.S. EPA regulations (40 CFR 86.144-90) using the following equation:

$$\text{Weighted g/mile} = 0.43 \times \frac{\text{Phase 1 grams + Phase 2 grams}}{\text{Phase 1 miles + Phase 2 miles}}$$

$$+ \ 0.57 \times \frac{\text{Phase 3 grams + Phase 2 grams}}{\text{Phase 3 miles + Phase 2 miles}}$$

20
[00134] After each aging set was completed, the catalysts were installed on the test vehicle and retested over the FTP test cycle to obtain deterioration information. The before and after aging FTP results were then compared to quantify a deterioration factor

for each catalyst. The FTP results, averaged by catalyst and aging condition, are given in

Table 11.

**TABLE 11. COLD-BAG AND WEIGHTED FTP RESULTS,
BEFORE AND AFTER AGING**

Test ID Catalyst	Aging Start	Emissions, grams				Fuel Economy, mpg
		THC	NMHC	CO	NO$_x$	
FTP Bag 1						
Engine Cat-E1	0-hr	0.75	0.70	5.72	1.84	22.3
Engine Cat-E2	0-hr	0.76	0.71	6.36	1.58	22.4
Engine Cat-E3	0-hr	0.67	0.62	5.23	1.66	22.6
FOCAS™ Cat-B1	0-hr	0.73	0.68	5.30	1.58	22.7
FOCAS™ Cat-B2	0-hr	0.78	0.73	6.68	1.56	22.2
FOCAS™ Cat-B3	0-hr	0.76	0.70	6.03	1.71	22.5
Engine Cat-E1	100-hr	0.94	0.87	8.49	2.47	23.2
Engine Cat-E2	100-hr	0.94	0.85	8.63	2.65	22.8
Engine Cat-E3	100-hr	0.99	0.91	8.70	2.56	22.9
FOCAS™ Cat-B1	100-hr	0.95	0.89	7.93	2.62	22.6
FOCAS™ Cat-B2	100-hr	1.01	0.94	8.10	2.44	22.3
FOCAS™ Cat-B3	100-hr	1.05	0.98	8.87	2.63	22.1
Weighted FTP Emissions Results, g/mi						**Weighted FE, mpg**
Engine Cat-E1	0-hr	0.050	0.044	0.387	0.168	23.2
Engine Cat-E2	0-hr	0.050	0.045	0.442	0.151	23.3
Engine Cat-E3	0-hr	0.045	0.040	0.381	0.154	23.4
FOCAS™ Cat-B1	0-hr	0.048	0.042	0.409	0.151	23.5
FOCAS™ Cat-B2	0-hr	0.052	0.046	0.503	0.149	23.2
FOCAS™ Cat-B3	0-hr	0.050	0.044	0.461	0.146	23.5
Engine Cat-E1	100-hr	0.069	0.058	0.695	0.253	24.1

Engine Cat-E2	100-hr	0.067	0.055	0.738	0.257	23.8
Engine Cat-E3	100-hr	0.070	0.060	0.631	0.249	23.0
FOCAS™ Cat-B1	100-hr	0.068	0.058	0.579	0.252	23.5
FOCAS™ Cat-B2	100-hr	0.075	0.062	0.732	0.268	23.3
FOCAS™ Cat-B3	100-hr	0.073	0.062	0.698	0.279	23.0

[00135] Fig. 15 shows the accumulated tailpipe mass hydrocarbon (THC) for all the FTP tests before and after aging. Fig. 15A is the degreened catalyst for which aged results are given in 15C. Fig. 15B is the degreened catalyst for which aged results are given in 15D.

5   A closer examination of the feedgas THC during cold-start (also shown in Fig. 15) reveals that it is the engine-out variation that causes the tailpipe variation. The modal emissions were then used to calculate vehicle air-fuel ratio (AFR).

[00136] Fig. 16 shows a comparison of the weighted FTP emissions for the converters before and after aging. Fig. 17 compares the average performance of the engine-aged

10   catalysts to the burner-aged catalysts. There was some degradation in THC, but the largest impact was on NO_x mass emission (largely due to the positioning of the catalyst on the vehicle). There also appeared to be very similar degradation impacts on both sets of catalysts. Table 12 gives the calculated deterioration factors for each of the regulated emissions by type of aging. The deterioration factor was calculated from the average

15   performance of each catalyst, using the following equation:

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$$1 + \left[\frac{M_{aged} - M_{unaged}}{M_{unaged}} \right]$$

TABLE 12. PERFORMANCE DETERIORATION FACTOR BY

CATALYST AND GROUP

Catalyst Group	Deterioration Factor		
	NMHC	CO	NOx
Catalyst E1	1.31	1.79	1.50
Catalyst E2	1.24	1.67	1.70
Catalyst E3	1.57	1.92	1.74
Average Engine Aged	1.37	1.80	1.65
Standard Deviation of Degradation	0.18	0.13	0.13
Catalyst B1	1.38	1.42	1.67
Catalyst B2	1.30	1.25	1.67
Catalyst B3	1.43	1.51	1.92
Average Burner Aged	1.37	1.39	1.75
Standard Deviation of Degradation	0.06	0.13	0.14

Reviewing Table 12 reveals that both aging methods produced equivalent impact on NMHC

emissions, but the burner-aged catalysts had less variation in calculated deterioration. There

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also appeared to be a difference in the NO_x deterioration factors, but the difference was not

statistically significant. Also, in examining the NO_x performance of each catalyst, it can be

seen that catalyst B3 appeared to have poorer NO_x performance, and sustained the greatest

deterioration for NO_x. This performance outlier will also appear in the AFR sweep data, and

5   will be presented in the next section.

B.   Accelerated Thermal Aging Cycle

[00137] The accelerated thermal aging procedure that was used in this work is the

published: Sims, G., Sjohri, S., "Catalyst Performance Study Using Taguchi Methods,"

10   SAE 881589; Theis, J., "Catalytic Converter Diagnosis Using the Catalyst Exotherm,"

SAE 94058; Ball, D., Mohammed, A., Schmidt, W., "Application of Accelerated Rapid

Aging Test (RAT) Schedules with Poisons: The Effects of Oil Derived Poisons, Thermal

Degradation, and Catalyst Volume on FTP Emissions," SAE 972846, each of which is

incorporated herein by reference. General Motors Rapid Aging Test version A (RAT-A)

15   cycle. One hundred hours of aging on the GM RAT-A cycle has been correlated to

100,000 miles of on-road operation for some platforms, but, precise miles to hours

correlation for experimental components and other platforms is unknown. However, 100

hours of aging on the GM RAT-A cycle does demonstrate a level of durability that is

accepted by industry. The following Table outlines the GM RAT-A aging schedule.

20

Mode No.	Description	Parameter Specification	Mode Length, sec
1	Closed-loop, Stoichiometric AFR	Inlet Temperature = 800°C	40

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2	Open-loop, Fuel-Rich Operation, Power enrichment	AFR ~ 13:1 (3%CO)	6
3	Open-loop, Fuel-Rich Operation, with Air Injection	AFR ~ 13:1 (3%CO) O2 = 3% (target a 160° - 200° exotherm - engine set first, burner set to match)	10
4	Closed-loop, Stoichiometric AFR with Air Injection	Stoichiometric Exhaust out of engine(burner) with continued air injection	4
Exotherm in Step 3 is measured on catalyst centerline, 1 inch deep			

The foregoing schedule describes exhaust and catalyst conditions, and does not specify how the engine is set to achieve those conditions; therefore, the same specifications that are used to set up the engine aging were used to set up the burner aging. During aging, exhaust gas AFR and temperature as well as catalyst temperatures were monitored at 1Hz and stored to file for post processing.

C.   Test Vehicle

[00138] The test vehicle for the program was a 1998 Honda Accord with 2.3L 4 cylinder VTEC engine, certified to California ULEV standards. The following Table provides vehicle information, and emissions certification data:

VIN	1HGCG6672WA165200
Engine Description	2.3L SOHC I-4 16-valve VTEC
Engine No.	F23A4-1016788
Engine Family	WHNXV02.3PL4
Transmission	4-speed automatic
Inertia Weight, lbs	3375
City Fuel Economy (cert)	23 mpg
Highway Fuel Economy (cert)	30 mpg

Emissions Certification Level	1998 California ULEV
FTP Certification Emission levels at 50,000 miles, grams/mile	
NMOG	0.0249
NO$_x$	0.0594
CO	0.2919

E.   Test Catalysts

[00139]   The catalysts used were 1997 Honda Civic ULEV production catalysts. Past experience with these catalysts has indicated that they generate very repeatable results and appear to be produced to very tight specifications. The Civic ULEV catalysts are manifold mounted and are supplied attached to exhaust manifolds. After receiving the parts, the catalysts were removed from the original mounting and then canned in "take apart" canisters to allow for easy installation on the aging and performance test stands and selection of the position of the catalyst on the vehicle. The catalyst position was moved from manifold mount to underbody in order to reduce exhaust gas temperatures into the catalysts, which should delay cold-start light-off (initiation of activation). Because this program's objective was to carefully compare the effects of thermal deactivation between two aging methods, the delayed light-off should prove beneficial in discerning the variations in catalyst aging more accurately.

F.   Engine Aging Stand

[00140]   Aging was performed using a Ford 7.5L V-8 engine. Oil consumption was also monitored during aging.

G.   FOCAS™ Rig

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[00141] The burner of the FOCAS™ Rig is a flexible fuel device, and was set to run on gasoline. Air flow provided to the burner was preset by the operator and did not vary throughout the test. The computer controlled the burner AFR by modifying the fuel

5   delivered to the air assisted injection system. The burner system created a very stable steady-state, constant pressure burn that, with gasoline, was capable of operating with a large turn-down ratio (range of AFR operation is 8:1 to 25:1). Continuous operation at stoichiometric could be conducted for at least two hundred hours, preferably for 1500 hours or more, with minimal maintenance. Burner operation could be adjusted to achieve

10   flows ranging from 20 to 70 SCFM (operated at 50 SCFM for this work), and the rig has a preprogrammed, cold-start simulation mode to allow the effects of cold-start to easily be added to an aging cycle.

[00142] Figure 9 shows measured, raw exhaust gas concentrations for the FOCAS™ system (50 SCFM) and a Ford 4.6L, V-8 engine (50 SCFM, 1500 rpm, 90 lb-ft, no EGR),

15   both operating on the same batch of CA Phase II fuel, at a slightly lean and a slightly rich steady-state exhaust A/F (measured using the Urban A/F method). The Urban AFR calculation method calculates exhaust AFR using the measured raw exhaust gas composition and fuel properties.

[00143] Figure 9 shows that the FOCAS™ Rig exhaust contains much lower THC and

20   NO_x levels, compared to a Ford 4.6L engine. The CO level is about half to three quarters of the engine level, and CO_2 and O_2 are approximately the same (as these two constituents are largely controlled by AFR, not combustion conditions). THC is low

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because the burner is highly efficient with steady, well vaporized fuel flow, and there are

no quench regions resulting in partial burn, as in an engine. NO_x is low because the

burner operates at near atmospheric pressure, unlike an engine in which NO_x is a result of

the high pressure and corresponding high peak temperature of combustion.

5   [00144] The control system for the FOCAS[TM] Rig consists of a LabVIEW-programmed

PC equipped with a touch screen monitor and a multi-function DAQ card, connected to

an SCXI chassis holding two SCXI 1120 multiplexing modules, one feed-through panel,

and an SCXI 1160 "relay module" to monitor and record system information, and to

control system electronics. Using the computer interface, the operator can switch power

10   to the blowers and fuel pump, as well as control the air assisted fuel injectors, burner

spark, oil injection, and auxiliary air, all with the touch of a finger.

[00145] System temperatures, mass air-flow for burner air, and the burner AFR were

measured and converted to engineering units. The software uses measured data to

calculate total exhaust flow and burner AFR, and to check conditions indicative of a

15   system malfunction. The burner AFR can be controlled as either open or closed loop,

maintaining the specified A/F. A/F control is achieved by varying the rate of fuel

delivered to the burner (modifying the pulse duty cycle of a fixed frequency control

waveform). Whenever necessary, open loop control was achieved by allowing an

operator to enter a fixed fuel injector pulse duty cycle (pulse width). Closed loop control

20   was achieved by measuring the actual burner A/F (using a UEGO sensor), comparing the

measured value to the A/F setpoint, and then adjusting the fuel injector duty cycle to

correct for the measured error. The front panel of the program was designed to allow

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users to input an aging cycle, and to run the test using a single screen. The controller

contained an 'auto start' and 'auto shutdown' options to allow for ease of operation.

After the burner fuel was activated, a set of safety checks automatically initialized and

monitored the burner for malfunction. While a test was in progress, the program collects

5   data at 4 Hz, stored data at 0.5 Hz, and displayed the catalyst inlet, bed, and outlet

temperatures and measured A/F ratio at 1 Hz, allowing the operator to review the overall

stability of the system.

[00146] Figure 18 shows the front panel of the control software. The front panel

depicted the layout of the actual test system and the location and value of the measured

10   data at each point in the system. Due to the potential danger of operating a gasoline-

fueled burner unattended for long periods of time, the system used three built-in safety

limits that checked for system malfunction. First, the heat exchanger outlet had to reach a

temperature greater than 100°C within four seconds after activation of fuel injection, and

had to maintain a minimum safety setpoint level during operation, which indicated that

15   the burner was properly ignited and remained lit. The third setpoint checked the catalyst

bed temperature to verify that the catalyst was not at a temperature that could be

detrimental to the experimental part. If any of the safety setpoints were compromised, the

computer was programmed to turn off all test systems, divert the blower and activate a

two minute N_2 purge into the burner head (to blow out the burner and suspend any

20   unburned fuel in N_2, thereby preventing a large exothermic reaction in the test piece), and

to display a bright red screen describing the condition at which the system was shut down,

along with the date and time, and data which were recorded at 4 Hz for ten minutes after a

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safety had been compromised. In addition, the N_2 purge system was also activated and a safety shutdown was followed when an electrical power loss was detected, thereby making it safe to operate the rig during questionable weather conditions.

B.   RAT-A Simulation on FOCAS™ Rig

[00147] The RAT-A cycle is characterized mainly by steady-state, stoichiometric operation and short thermal excursions (specifications given previously). The thermal excursions were created by operating rich, to generate about 3 percent carbon monoxide (CO), while injecting secondary air (about 3 percent oxygen, O_2) in front of the catalyst. The excess reductants and oxidants reacted in the catalyst, releasing the chemical energy in the form of heat. The catalyst inlet temperature and exhaust gas flow rate were also used to specify the test cycle setup. The flow was specified in scfm, 70 scfm was used in this work.

[00148] On the engine, the flow specification was set up by adjusting engine speed. The gas temperature at the inlet to the catalyst was achieved by adjusting engine load (throttle position) during the steady-state, stoichiometric portion of the cycle. The thermal excursion was created by adjusting engine operating AFR during the rich portion of the cycle, and adjusting air injection to achieve the 3 percent CO and O_2 specification.

[00149] On the burner, flow was modified by changing the setting of the burner bypass valve, and catalyst inlet gas temperature was adjusted by increasing or decreasing the number of heat exchanger units, the flow through the units, and air cooling of the exhaust section between the heat exchanger outlet and catalyst inlet. Coarse gas inlet temperature control was achieved with the heat exchanger, while fine control came from air cooling of

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the exhaust section.

[00150] Figure 19 shows measured exhaust gas and catalyst bed temperatures during

engine and burner aging. Also shown is the measured AFR at engine and burner outlet.

The upper left corner shows the RAT-A cycle on the engine, and the upper right corner

5   shows the RAT-A cycle on the FOCAS™. The bottom two graphs show the burner and

the engine characteristics compared directly to each other. The outlet thermocouples are

in slightly different locations, and should not be compared.

[00151] The bottom right graph shows a comparison of the catalyst inlet and bed

temperatures during the cycle. The bed temperatures were very similar between the two

10   aging systems. However, the effect of the fuel cut and the air injection produced different

inlet temperature profiles between the two systems. The burner showed the drop in

temperature (from to the rich excursion) more quickly, but then showed a higher

temperature into the catalyst during the rich with air portion of the cycle. This was

indicative that some of the reactants were burning in the pipe before entering the catalyst.

15   This burning may be a result of differences in the way the air was injected between the

two systems, and it results in one effect, the potential impact of which is not fully

understood. The effect is that the peak temperature in the catalyst was observed at 0.5" in

the burner catalyst, as opposed to 1.0" in the engine catalyst (compare Fig. 19A and 19B).

Fig. 19C shows the measured exhaust AFR and catalyst bed temperature (1.0" depth).

20   Comparing the AFR control, it can be seen that the burner had much tighter AFR control

than the engine. The other characteristic noted in the graph is that during the thermal

excursion the burner went richer than the engine. This was necessary to overcome the

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burning in the pipe, and to maintain the thermal excursion in the catalyst. Overall, the difference in the ability to generate reactants and resulting catalyst bed temperature between the two systems was very small.

[00152] However, there was one control factor that began to appear as a problem for the burner system as the program progressed. The problem was slight variations in catalyst inlet temperature from day-to-day and day-to-night. The cause of the problem appeared to be variations in the air cooling of the section between the heat exchanger and catalyst inlet. The fine tuned catalyst inlet temperature was controlled by varying the amount of exhaust insulation, and the placement of the cooling fans at the beginning of each test. However, as the test progressed, it was found that variations in cooling tower water and the air conditions in the new cell created conditions that could vary substantially day-to-night, and day-to-day. This allowed the catalyst inlet temperature to vary by up to 20°C. For this reason, a closed-loop fan control was created and embedded in the FOCAS™ controller. Figure 10 shows a schematic of the closed-loop fan control created for catalyst inlet temperature. The controller output varies the speed of the cooling fans from off, to low, to high.

Example 6

[00153] Seven general design criteria/guidelines were used to design this preferred fuel injector. These criteria were:

20   1)   Pressure in the air channel could not exceed pressure in the fuel channel or fuel flow would be interrupted. Assuming the burner flow is steady-state (a reasonable assumption):

$$\textit{For Air:} \quad \frac{P_{1_A}}{A_{1_A}} \times A_{2_A} = P_{2_A} \qquad\qquad \textit{For Fuel:} \quad \frac{P_{1_f}}{A_{1_f}} \times A_{2_f} = P_{2_f}$$

2) Desired fuel inlet pressure (based on fuel pump specifications) is 40 psig $< P_f < 60$ psig.

3) The area of the fuel jets must provide adequate fuel flow for the required flow range, in the given operating pressure range.

4) The size of the fuel holes must be a standard drill bit size, and must be large enough to allow machining without excessive difficulty.

5) Fuel/Air spray should aim for outer air shroud convergence to keep the burner flame off the combustor wall as long as possible.

6) Direct point of fuel jet convergence behind air shroud. Adjustment of P_A can be used to vary the position of the fuel spray relative to the air shroud.

7) Keep interaction point of the fuel and the air jet at the center of the combined outlet hole to prevent driving the fuel spray to the inner wall of the injector. This would lead to dripping, and coking of the face of the injector.

8) The degree of atomization and stability will be determined visually using the quartz combustor. The assessment was based on the blueness of the flame (orange flames indicating sooty conditions), the soot forming potential (assessed by examining the injector, combustor, heat exchanger and exhaust pipe), and the stability of the flame (assessed using a linear AFR sensor).

[00154] Since the burner is designed to operate predominantly at stoichiometric, the

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required fuel flow can be calculated using the required total exhaust gas flow and the

stoichiometric AFR of the fuel used for aging. The following analysis presents the

calculation of the required fuel flow for the burner operating at stoichiometric, with a

total exhaust flow of 70 SCFM.

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$$m_{exh} = 70 \text{ SCFM} = 2.3015 \text{ kg/min}$$
$$m_{fuel} = m_{exh} \times AFR_{stoich}^{-1} \times 1 \text{ lb}/0.45359 \text{ kg} \times 60 \text{min/hr}$$
$$m_{fuel} = 21.28 \text{ lb/hr at stoichiometric}$$
$$m_{air} = m_{fuel} \times (AFR_{avg} / AFR_{stoich})$$
$$AFR_{avg} = (16/60 \times 13) + (44/60 \times 14.4) = 14.03 \quad \text{RAT-A cycle}$$

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$$m_{air} = 65.1 \text{ SCFM}$$

Therefore, the rate of energy consumption of the burner over the cycle is:

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$$Q = m_{fuel} \times \text{Energy content of fuel}$$
$$Q = m_{fuel} \times 18,400 \text{ BTU/lb} = 21.28 \text{ lb/hr} \times \text{hr}/3600\text{sec} \times 18,400 \text{ BTU/lb} \times 1.055 \text{ KJ/BTU}$$
$$Q = 115 \text{ kW}$$

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[00155] Referring to Figure 20, the distance l_1 is the radius of the combustion tube 210,

and l_2 is the distance to impact with the wall. The distance l_2 can be calculated using

geometry, but then is corrected for interaction with the fuel jet (which tends to lengthen

l_2) and the inner swirl jets 242 (which tend to shorten l_2). The inner swirl jets 242 have

25   the greatest impact. The final angle for X,X' is a function of fuel shearing and

atomization (which is improved with lower X,X') and preventing impact with the wall of

the combustion tube 210 by directing the fuel spray into the area where the outer swirl

jets 253 in Fig. 3 converge (about four to five inches from the face of the swirl plate).

These outer swirl jets 253 help to keep the hottest part of the flame off the inner wall of

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the combustion tube 210, which enables the burner to run stoichiometric for extended

periods of time. Table 1 shows calculated impact of the fuel spray with the inner wall of

the combustion tube 210, with and without swirl jet interaction. From these data, two

fuel injectors were built, E-62 and E-76 (where the number refers to the angle X,X' in

5   degrees).

Table 1

Air Injection Angle, X,X'	Calc. Impact Distance, No Interaction, in.	Observed Impact, in.	Calc. Impact Distance with Medium Interaction, in.
60	2.75		2.5
61	2.88		2.57
62	3.03		2.64
63	3.18		2.71
64	3.34		2.8
65	3.52		2.89
66	3.71		2.98
67	3.92		3.08
68	4.14	3.25 - 3.5	3.2
69	4.38		3.32
70	4.65		3.45
71	4.95		3.6
72	5.27		3.76
73	5.63		3.94
74	6.04		4.14
75	6.5		4.37
76	7.02		4.64
77	7.62		4.94
78	8.32	5	5.29
79	9.15		5.7
80	10.13		6.19

[00156] From these data, two fuel injectors were built, with an angle "α " in degrees of

10   62 and 76 (sometimes referred to hereafter as "E-62" and "E-76," respectively). After the

injectors were built, they were tested in the FOCAS™ rig. The quality of the flame was

assessed using three criteria: a visual measure of smoke in the exhaust, soot on the

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combustor, heat exchanger, and catalyst; the appearance of the flame (blueness and

transparency); and the location of flame impact with the burner wall. Additionally, the

stability of the flame was assessed visually and through measured AFR feedback using a

UEGO sensor. The completeness of the burn was also quantified by measuring the

exotherm in the catalyst at 70 scfm and stoichiometric. The exotherm in the catalyst was

an indicator of the level of unburned fuel. For a gasoline engine at these conditions, the

catalyst exotherm (using this test catalyst) was about 60°C. The final FOCAS™ injector

gave about 50 to 60°C exotherm. The burner conditions during the visual analysis were:

	E-68-062	E-76-062
Fuel Injection Pressure:	50 psig	50 psig
Air Injection Pressure:	100 psig	55 psig
Burner Flow:	70 scfm	70 scfm

[00157] The visual quality of both of these flames was very acceptable (no soot build-up,

no smoke) and the catalyst bed temperatures were in an acceptable range. E-68-062

showed a very blue flame, indicative of excellent atomization; but the flame impinged on

the wall very close to the swirl plate, and experience dictated that this type of impact

would damage the burner wall. This led to using E-76-062, which did not have as high a

flame quality for blueness and transparency, but extended the impact of the flame with

the burner wall to an area that would not damage the combustor wall. Although some

flame quality was sacrificed for combustor durability, E-76-062 showed a very high

quality flame for blueness and transparency compared to commercially available injectors

that were tested.

[00158] Figure 21 shows a graph of the calculated fuel spray impacts. Generally thermal

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aging damaged the catalyst washcoat in the front one inch of the catalyst, which impacted the light-off behavior of the catalyst. Figure 22 shows the measured mass emission during the cold-start phase of the FTP. It can be seen that there are some differences in NMHC, CO and NOx mass emissions. Figure 29 shows the measured catalyst bed temperature during cold-start. Examining Figure 29 indicates that beginning during the first acceleration, and continuing from that point, there was a separation in the catalyst bed temperature between the aged and unaged catalysts. Both the engine- and the burner-aged catalysts showed comparable performance before and after aging. This difference in temperature is an indicator that the aged catalysts were operating with lower efficiency.

Figure 22 shows the accumulated modal mass emission of THC and NO_x before and after aging. It can be seen in these figures, that there is indeed lower activity in the aged converters, and it appears that the engine- and burner-aged catalysts had very similar performance.

Example 7

Statistical Analysis of FTP Performance Data

[00159] Six catalysts were examined in this study to determine differences in emissions based on the type of aging performed. Three catalysts were aged on an engine and three were aged on the FOCAS™. Each catalyst was aged 100 hrs. FTPs were run on all six catalysts in which NO_x, THC, NMHC, and CO measurements were taken before and after the aging process. Multiple FTPs were run on each catalyst. Table 13 lists the number of FTP runs made for each catalyst in this study.

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TABLE 13. CATALYST FTP STATISTICAL DATA MATRIX

		Engine Aging			FOCAS™ Aging		
Catalyst		1	2	3	4	5	6
Aging Hrs	0	2	2	2	2	1	2
	100	2	2	3	2	1	2

[00160] In order to compare the effect of aging type on emissions, a repeated measures analysis of variance statistical model was used. This model contained the following factors:

- Aging Type (engine or FOCAS)

- Catalyst nested within aging type (each catalyst was only aged by one method)

- Aging Time (0 and 100 hrs)

- Aging Type x Aging Time interaction

[00161] Each of the four emissions was analyzed by this model individually. Table 14 lists the results of the repeated measures model. The hypothesis tested for each factor was whether the average emission for each level in that factor is significantly different. For example, the Aging Type factor compares the average NO_x between the catalysts aged in the engine and the catalysts aged on the FOCAS™ over all the time periods. For each factor in the model, a p-value is listed which indicates the probability of accepting the hypothesis that there is no significant difference in the average emissions between the factor levels. All statistical comparisons were made at the 5 percent level of significance. Thus, p-values less than 0.05 indicate statistically significant differences in the average

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emissions for that factor.

TABLE 14. REPEATED MEASURES ANOVA MODEL RESULTS

Factor	NO_x	THC	NMHC	CO
Aging Type	0.4023	0.5688	0.2221	0.5218
Catalyst Nested in Aging Type	0.5792	0.7303	0.8488	0.0596
Aging Time	0.0001	0.0001	0.0001	0.0001
Aging Type x Time Interaction	0.3022	0.5712	0.9922	0.0026

The conclusions based on the repeated measures ANOVA model were as follows:

- There was no significant difference in the average emissions between the catalysts aged on the engine and the catalysts aged on the FOCAS over both time periods.

- There was no significant difference in the average emissions among the three catalysts aged on the engine over both time periods.

- There was no significant difference in the average emissions among the three catalysts aged on the FOCAS over both time periods.

- There was a statistically significant difference in the average emissions between the catalysts at the zero hours and the catalysts at the 100 hours of aging.

- There was no significant difference in the average emissions between the aging type and the aging time for the NOx, THC, and NMHC emissions. However, there was a statistically significant difference in the average CO between the aging type and the aging time. In this case, the catalysts aged on

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the engine demonstrated a significantly greater increase in CO from zero

hours to 100 hours than seen on the catalysts aged on the FOCAS™.

Plots of the THC, NMHC, NO_x, and CO emissions by catalyst and aging period are

illustrated in Fig. 25 - Fig. 28, respectively. On the x-axis tickmark labels, the first letter

represents the aging type (B=FOCAS bench, E=engine), the second digit represents the

catalyst number, and the last number represents the aging time (0 or 100 hours).

Example 8

Postmortem Catalyst Evaluations

[00162] After all the performance analyses were completed, the catalysts were

disassembled, the center (one-inch diameter, one-inch deep) of each catalyst was cored

for surface area and composition analysis. The two analyses run were BET (Bruhauer-

Emmett-Teller) for assessment of surface area and porosity, and PIXE (Proton-Induced

X-Ray Emissions) for compositional analysis.

[00163] The BET test provided information on the surface area of the substrate and

washcoat. This analysis was correlated to thermal degradation. PIXE provided

information on the composition of the substrate, washcoat, and any deposits on the

surface of the catalyst. PIXE analysis provided information on the differences in the

deposits on the catalysts between the engine and the burner (which provided oil-free

aging).

Table 15 gives the results of the PIXE analysis, for select elements.

TABLE 15. PIXE ANALYSES RESULTS FOR SELECT ELEMENTS

Element	Mass Concentration, Wt%					
	E1	E2	E3	B1	B2	B3
P, ppm	<674	<723	<766	<715	<758	
Zn, ppm	326	279	316	13	13	
Rh, ppm	0.672	0.650	0.731	0.626	0.662	
Pd, %	0.187	0.208	0.219	0.183	0.201	NOT RUN
Pt, %	0.187	0.208	0.219	0.183	0.201	
Ce, %	2.883	3.028	3.314	2.954	3.282	

[00164] Table 15 highlights two basic categories of elements, components of oil, and elements found in the catalyst washcoat. The PIXE analysis showed that the washcoat materials (Rhodium, Palladium, Platinum, Cerium) were fairly consistent among the five catalysts tested. In looking at the Zinc (Zn) deposits between the groups it was seen that the engine catalysts had substantially more Zn. Phosphorus (P) appeared to be below the detection limits (about 700 ppm). However, P is added to oil as an anti-wear additive and generally comes in the form of ZDP; and field deposits on catalysts have shown Zn:P weight ratios of about 0.5 - 0.75. This would imply that there is probably some P on the engine catalysts, perhaps in the range of 400 - 600 ppm, which would be below the detection limit used in this analysis.

[00165] The final analysis run on the catalysts was a BET analysis for specific surface area. A catalyst in good condition has a high surface area. As the catalyst ages it loses surface area thermally through agglomeration (migration of the precious metal) and sintering (melting), and non-thermally through physical blockage of pores by deposits. Table 16 gives the BET surface area analysis results.

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TABLE 16. BET SURFACE AREA ANALYSIS FOR AGED CATALYSTS

Catalyst	Condition	BET Surface Area, m^2/g
E1	100 RAT-A - Engine Aged	11.50 ± 0.22
E2	100 RAT-A - Engine Aged	11.46 ±0.93
E3	100 RAT-A - Engine Aged	11.91 ± 0.13
B1	100 RAT-A - Burner Aged	12.84 ± 0.72
B2	100 RAT-A - Burner Aged	13.32 ± 0.34
B3	100 RAT-A - Burner Aged	12.47 ±0.22

[00166] The BET analysis shows a difference in final specific surface area between the two aging methods, with the engine aged parts having a lower surface area compared to the burner-aged parts. The fresh catalyst specific surface area was probably about 18-25 m2/g (although a fresh catalyst was not analyzed as part of this program). This difference in the surface area between engine- and the burner-aged catalyst is not large, but may be attributable to one or more of the following: the small amounts of oil-related deposits observed in the engine aged catalysts; the increased mass due to the deposits (since the surface area is measured as $m^2/gram$); and/or, the beginning of catalyst pore blockage, as occurs in non-thermal deactivation when deposits begin to coat the surface of the catalyst. It is generally accepted that oil deposits require a minimum mass before the deposits significantly affect catalyst performance.

[00167] The post-mortem analysis showed that the FOCAS™ aging provided thermal aging in the absence of non-thermal aging (i.e. oil deposits), thereby creating a means for the definitive isolation of thermal and non-thermal aging effects.

[00168] The simulated RAT-A cycle on the FOCAS™ burner system was compared to

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the cycle on the engine. It was demonstrated that the burner can be used to generate a very similar thermal profile inside the catalyst when compared to the profile generated by the engine. The shape of the thermal excursion was reproduced, and the AFR into the catalyst could be controlled and reproduced. One difference that was noted between the two systems was that there appeared to be some burning of the reactants in the exhaust pipe, prior to entering the catalyst, in the burner system. This resulted in a slight shift forward of the peak in the location of the peak temperature during the thermal excursion.

Example 9

[00169] The methodology was tested by using the FOCAS™ burner system to simulate the General Motors Rapid Aging Test version A (RAT-A) cycle. During the testing portion of the program, six catalysts were aged for 100 hours on the RAT-A cycle; three on an engine aging stand, and three on the FOCAS™ burner system. The catalyst performance at defined intervals and at the conclusion of the aging was measured and compared between the two systems. In addition, the variation and repeatability of the temperature and AFR control of each system were assessed and compared.

[00170] The performance evaluations consisted of comparing the regulated emissions across the Federal Test Procedure (FTP) and using an engine-based catalyst performance evaluation rig to measure the catalyst conversion efficiency as a function of exhaust air/fuel ratio (AFR) and catalyst light-off temperature.

[00171] The FTP performance evaluations showed that the burner and the engine produced equivalent aging effects, resulting in deterioration factors for THC, CO, and NOx that were not statistically different between the two methodologies. There was no

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significant difference in the average emissions between the aging type and the aging time

for the NOx, THC, and NMHC emissions on the FTP test. However, there was a

statistically significant difference in the average CO between the aging type and the aging

time. In this case, the catalysts aged on the engine demonstrated a significantly larger

5   increase in CO from zero hours to 100 hours than was seen on the catalysts aged on

FOCAS™. The evaluations revealed that the two methodologies produced equivalent

results near stoichiometric (where a gasoline engine is tuned to run). However, as the

AFR deviated from stoichiometric to the rich side it was observed that burner aging had a

slightly more severe aging effect on THC and CO.

10   [00172] The final catalyst evaluations involved coring the catalysts, and analyzing the

surface area and composition. The two analyses run were BET for assessment of surface

area and porosity, and PIXE for compositional analysis. The BET test provides

information on the surface area of the substrate and washcoat. PIXE provides information

on the composition of the substrate, washcoat, and any deposits on the surface of the

15   catalyst. PIXE analysis can provide information on the differences in the deposits on the

catalysts between the engine and the burner (which provides oil-free aging). It was found

that the catalysts were composed of very similar levels of washcoat, but that the

FOCAS™-aged catalysts had an obvious absence of oil derived deposits. However, the

levels of oil deposits found on the engine aged catalysts were small, and it is likely that

20   deposits did not impact catalyst performance in this study. However, as an engine ages,

oil consumption will increase, adding a variable oil poisoning component to the catalyst

aging. It is generally accepted that oil deposits require a minimum mass before the

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deposits significantly affect catalyst performance. The BET analysis showed a difference

in final specific surface area between the two aging methods, with the engine aged parts

having a lower surface area compared to the burner aged parts. The reduced surface area

could be a result of the increased core mass due to the deposits (since the surface area is

5   measured as m^2/gram). The reduced surface area could also be the beginning of catalyst

pore blockage, as occurs in non-thermal deactivation when deposits begin to coat the

surface of the catalyst. It could also be a result of a combination of the two effects.

[00173] Overall, it was found that the FOCAS™ burner system provided a flexible

means for simulating the engine aging cycle, and produced thermal aging results

10   equivalent to the engine cycle. The post-mortem analysis showed that the FOCAS™

aging provides thermal aging in the absence of non-thermal aging (i.e. oil deposits),

thereby creating a means for the definitive isolation of thermal and non-thermal aging

effects. Some advantages that using a burner offers over an engine for aging include:

very tight AFR control (±0.02 AFR), very broad range of stable AFR operation (8:1 to

15   25:1), few moving parts (a blower and a fuel metering valve), and minimal adjustments to

achieve setpoints. Also, a burner can be run at very high temperatures without severely

damaging the system components, making for a low cost, low risk simulation of very high

temperature cycles.

[00174] Persons of ordinary skill in the art will recognize that many modifications may

20   be made to the present application without departing from the spirit and scope of the

application. The embodiment described herein is meant to be illustrative only and should

not be taken as limiting the application, which is defined in the claims.

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We claim:

1   1.   A non-engine based exhaust component rapid aging system (NEBECRAS)

2   comprising a combustor in fluid communication with an air supplier, a fuel supplier, and

3   a catalytic converter, said combustor being adapted to provide substantially continuous

4   and effective stoichiometric combustion of a fuel feedstream to produce an exhaust

5   product.

1   2.   The NEBECRAS of claim 1 wherein said combustor comprises a

2   combustion tube comprising an inner wall, and said combustor produces a flowpath

3   comprising at least a first collapse, an expansion, and a second collapse.

1   3.   The NEBECRAS of any of claims 1 or 2 wherein said first collapse and

2   said second collapse are at a distance which is substantially the same as said inner

3   diameter.

1   4.   The NEBECRAS of any of claims 1, 2, or 3 wherein said combustor

2   comprises a swirl plate comprising a substantially central bore comprising an air assisted

3   fuel spray nozzle.

1   5.   The NEBECRAS of any of claims 1-4 further comprising at least one

2   igniter along said inner wall of said combustor tube, said at least one igniter being located

3   at said expansion.

1   6.   The NEBECRAS of any of claims 1-5 wherein said air flowpath further

2   comprises a second expansion and a third collapse and said combustor further comprises

3   at least a second igniter located at said second expansion.

1   7.   The NEBECRAS of any of claims 1-6 wherein said combustor produces a

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2   flame, and said swirl plate has a thickness sufficient to fix said air flowpath and to create

3   an air shroud adjacent to said air assisted fuel spray nozzle effective to prevent said flame

4   from attaching to said air assisted fuel spray nozzle.

1   8.   The NEBECRAS of claim 7 wherein said thickness is about ½ inch or

2   more.

1   9.   The NEBECRAS of any of claims 1-8 wherein said swirl plate comprises:

2   an inner set of turbulent jets;

3   first and second outer sets of turbulent jets located radially outward from said

4   inner set of turbulent jets, each of said inner set of turbulent jets and

5   second and third outer sets of turbulent jets being adapted to direct air

6   inward, toward said bore; and

7   an inner set of swirl jets; and,

8   an outer set of swirl jets located radially outward from said inner set of swirl jets,

9   said inner set of swirl jets and said outer set of swirl jets being adapted to

10   direct air outward toward said inner wall of said combustor tube.

1   10.   The NEBECRAS of any of claims 1-9 wherein

2   said combustor comprises a fuel injection side and a burner side and, upon

3   activation, produces a flame at said burner side, said first and second outer

4   set of turbulent jets being adapted to prevent said flame from remaining in

5   constant contact with said inner wall of said combuster tube;

6   said inner set of turbulent jets are adapted to produce a first area on said fuel

7   injection side having a pressure sufficiently low to draw fuel into said

8   combustion tube, said inner set of turbulent jets also producing a second

9   area on said burner side having a pressure sufficiently high to prevent said

10   flame from attaching to said air assisted fuel spray nozzle, said pressure

11   also being sufficiently high to shear fuel droplets as they enter said flame;

12   and,

13   said inner swirl jets being adapted to direct air against said inner wall of said

14   combuster tube downstream of said swirl plate at a location intersecting a

15   spray of fuel from said air assisted fuel spray nozzle.

1   12.   The NEBECRAS of any of claims 1-11 wherein said inner set of turbulent

2   jets and said first and second outer set of turbulent jets each comprise four individual jets

3   spaced apart at approximately 90° relative to one another along a circle located

4   concentrically outward from said bore.

1   13.   The NEBECRAS of any of claims 1-12 wherein said swirl plate has a plate

2   surface, and said second set of swirl jets comprises an outer set of swirl jets and an inner

3   set of swirl jets having an angle relative to said plate surface of about 25°.

1   14.   The NEBECRAS of any of claims 1-13 wherein said swirl plate has a

2   longitudinal axis, and said turbulent jets are at an angle with respect to said longitudinal

3   axis of about 43.5°.

1   15.   The NEBECRAS of any of claims 1-14:

2   wherein said swirl plate comprises a fuel injection side and a burner side and said

3   combustor produces a flame at said burner side; and

4   said air assisted fuel spray nozzle comprises a flanged male fitting adapted to mate

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5   with a central bore in said swirl plate, said flanged male fitting defining at

6   least one air injection bore in fluid communication with both a source of

7   air and a source of fuel;

8   said air assisted fuel spray nozzle further comprising at least one fuel injection

9   bore in fluid communication with both said source of fuel and with said air

10   injection bore.

1   16.   The NEBECRAS of any of claims 1-15 wherein:

2   said flame comprises a hot region comprising maximum temperatures;

3   said air injection bores have a longitudinal axis at an air injection angle relative to

4   a surface of said air assisted fuel spray nozzle at said fuel injection side;

5   and,

6   said air injection angle is effective to provide sufficient fuel shearing and

7   atomization as well as to prevent said hot region from impacting said inner

8   wall of said combustor.

1   17.   The NEBECRAS of any of claims 1-16 wherein said air injection angle is

2 from about 65° to about 80°.

1   18.   The NEBECRAS of any of claims 1-17 wherein said fuel injection bores

2 have a longitudinal axis at an angle relative to a surface of said air assisted fuel spray

3 nozzle at said fuel injection side, said angle being from about 60° to about 80°.

1   19.   A swirl plate for a non-engine based exhaust component rapid aging

2 system comprising:

3   a substantially central bore;

4   an inner set of turbulent jets;

5   first and second outer sets of turbulent jets located radially outward from said

6   inner set of turbulent jets, each of said inner set of turbulent jets and

7   second and third outer sets of turbulent jets being adapted to direct air

8   inward in the direction of said central bore;

9   an inner set of swirl jets; and,

10   an outer set of swirl jets located radially outward from said inner set of swirl jets,

11   said inner set of swirl jets and said outer set of swirl jets being adapted to

12   direct air toward an outer periphery of said swirl plate.

1   20.   The swirl plate of claim 19 wherein said inner set of turbulent jets and said

2   first and second outer set of turbulent jets each comprise four individual jets spaced apart

3   at approximately 90° relative to one another along a circle located concentrically outward

4   from said bore.

1   21.   The swirl plate of any of claims 19-20 wherein said swirl plate comprises a

2   plate surface, and said second set of swirl jets comprises an outer set of swirl jets and an

3   inner set of swirl jets having an angle relative to said plate surface of about 25°.

1   22.   The swirl plate of any of claims 19-21 wherein said swirl plate has a

2   longitudinal axis, and said turbulent jets are at an angle with respect to said longitudinal

3   axis of about 43.5°.

1   23.   A air assisted fuel spray nozzle comprising a fuel injection side and a

2   burner side, said air assisted fuel spray nozzle comprising:

3   a flanged male fitting adapted to mate with a central bore in said swirl plate, said

4   flanged male fitting defining at least one air injection bore adapted to

5   provide fluid communication with both a source of air and a source of

6   fuel;

7   said air assisted fuel spray nozzle further comprising at least one fuel injection

8   bore adapted to provide fluid communication with both said source of fuel

9   and with said air injection bore.

1   24.   The air assisted fuel spray nozzle of claim 23 wherein said air injection

2 angle is from about 65° to about 80°.

1   25.   The air assisted fuel spray nozzle of any of claims 23-24 wherein said fuel

2 injection bores have a longitudinal axis at an angle relative to a surface of said air assisted

3 fuel spray nozzle at said fuel injection side, said angle being from about 60° to about 80°.

1   26.   A NEBECRAS for aging a catalytic converter comprising:

2   catalytic converter means;

3   combustion means in fluid communication with said catalytic converter means,

4   said combustion means being effective to provide substantially continuous

5   stoichiometric combustion of automotive fuel;

6   fuel injection means in fluid communication with said combustion means; and,

7   lubricant injection means in fluid communication with said catalytic converter

8   means.

1   27.   The NEBECRAS of claim 26 wherein said combustion means comprises

2 a swirl plate means.

1   28.   The NEBECRAS of any of claims 26-27 further comprising

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2   data acquisition means;

3   air supply means in fluid communication with said combustion means; and,

4   heat exchanger means in fluid communication with said combustion means.

1   29.   A NEBECRAS for aging a catalytic converter comprising:

2   a burner adapted to provide substantially continuous and effective stoichiometric

3   combustion of a feedstream to produce an exhaust product;

4   a fuel injector system in fluid communication with said burner;

5   a catalytic converter in fluid communication with said exhaust product.

1   30.   The NEBECRAS of claim 29 further comprising a lubricant injection

2   system in fluid communication with said catalytic converter.

1   31.   The NEBECRAS of any of claims 29-30 further comprising a data

2   acquisition system adapted to provide substantially continuous fuel metering control.

1   32.   The NEBECRAS of any of claims 29-31 wherein said data acquisition

2   system is further adapted to provide substantially continuous catalyst safety monitoring.

1   33.   The NEBECRAS of any of claims 29-31 further comprising a data

2   acquisition system adapted to provide substantially continuous fuel metering control.

1   34.   The NEBECRAS of any of claims 29-33 wherein said burner comprises a

2   swirl plate.

1   35.   The NEBECRAS of any of claims 29-34 wherein said burner comprises:

2   a plenum chamber;

3   a combustion tube defining a bore; and,

4   a swirl plate separating said plenum chamber and said combustion tube, said swirl

5   plate comprising an air assisted fuel spray nozzle assembly means and

6   being adapted to produce a pattern of collapsed conical and swirl flow in

7   said combustion tube that defines at least one flowpath along said bore,

8   preferably at least three flowpaths.

1   36.   The NEBECRAS of any of claims 29-35 wherein said swirl plate

2 comprises an air assisted fuel spray nozzle assembly in fluid communication with an air

3 supply and a fuel supply, said air supply and said fuel supply being adapted to provide

4 atomized fuel to said combustion means.

1   37.   The NEBECRAS of any of claims 29-36 wherein said swirl plate

2 comprises an air assisted fuel spray nozzle assembly in fluid communication with an air

3 supply and a fuel supply, said air supply and said fuel supply being adapted to provide

4 atomized fuel to said combustion means.

1   38.   The NEBECRAS of any of claims 29-37 wherein said bore comprises an

2 inner diameter, and a pattern produced by said flowpaths collapses and expands at

3 intervals that are substantially equal to said inner diameter of said burner.

1   39.   The NEBECRAS of any of claims 29-38 wherein said inner diameter of

2 said burner is about 4 inches, and said pattern collapses and expands at intervals of about

3 4 inches.

1   40.   The NEBECRAS of any of claims 29-39 further comprising at least one

2 igniter in fluid communication with said at least one flowpath.

1   41.   The NEBECRAS of any of claims 29-40 wherein said lubricant injection

2 system is adapted to provide an atomized spray of lubricant comprising droplets having a

3   diameter sufficiently small for said droplets to vaporize upon exposure to said burner.

1   42.   The NEBECRAS of any of claims 29-41 wherein said diameter of said

2   droplets is about 80 microns or less.

1   43.   The NEBECRAS of any of claims 29-42 wherein said diameter of said

2   droplets is about 20 microns or less.

3

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FIG. 1

FIG. 2A

FIG. 2B
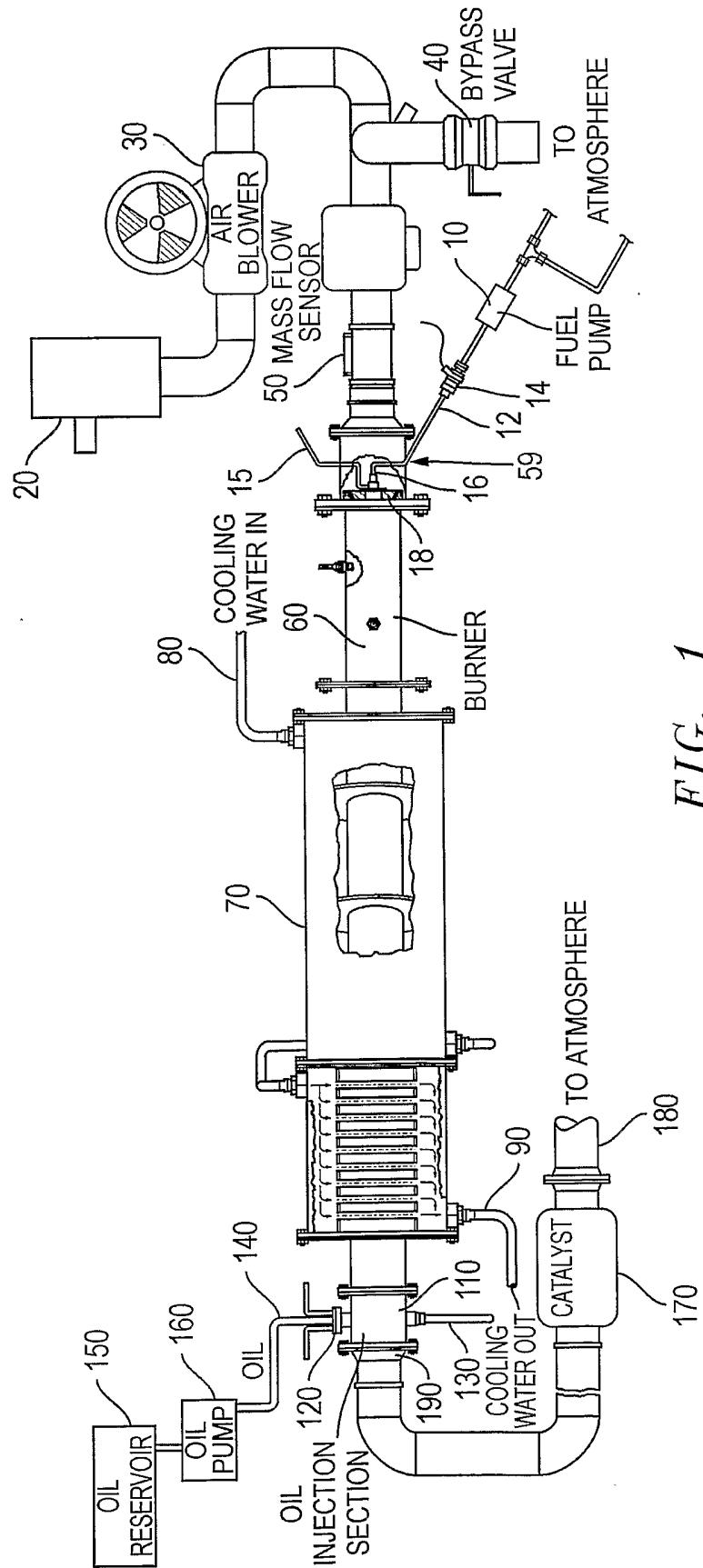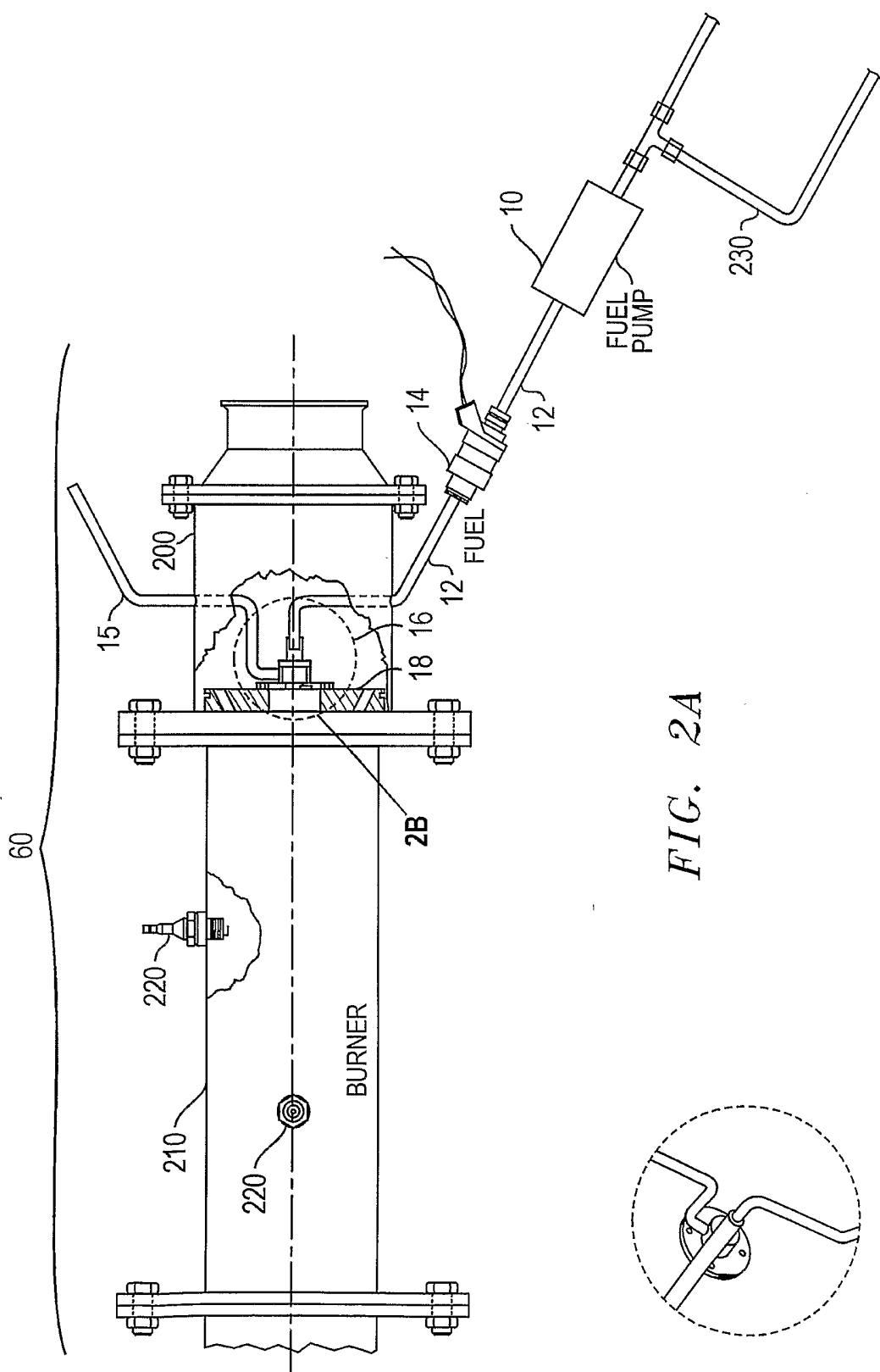
3/28
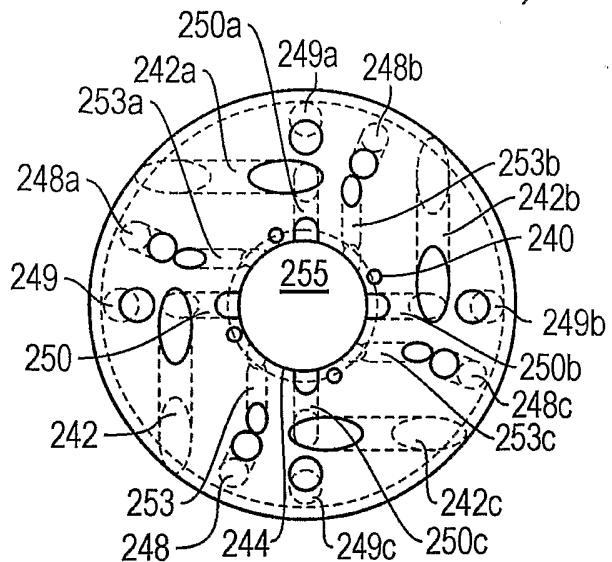
FIG. 3A
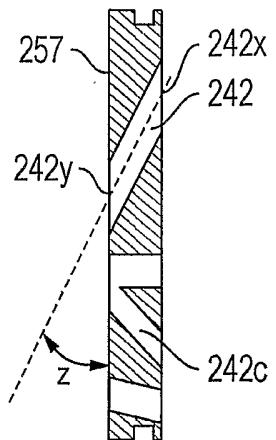
FIG. 3B

FIG. 3C
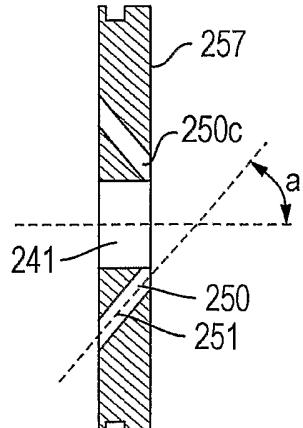
FIG. 3D
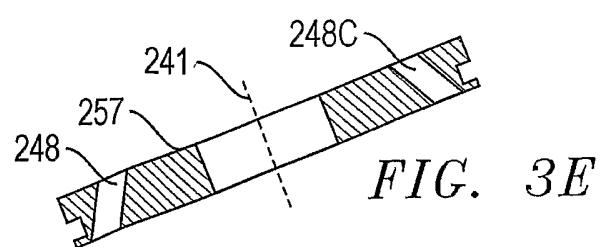
FIG. 3E

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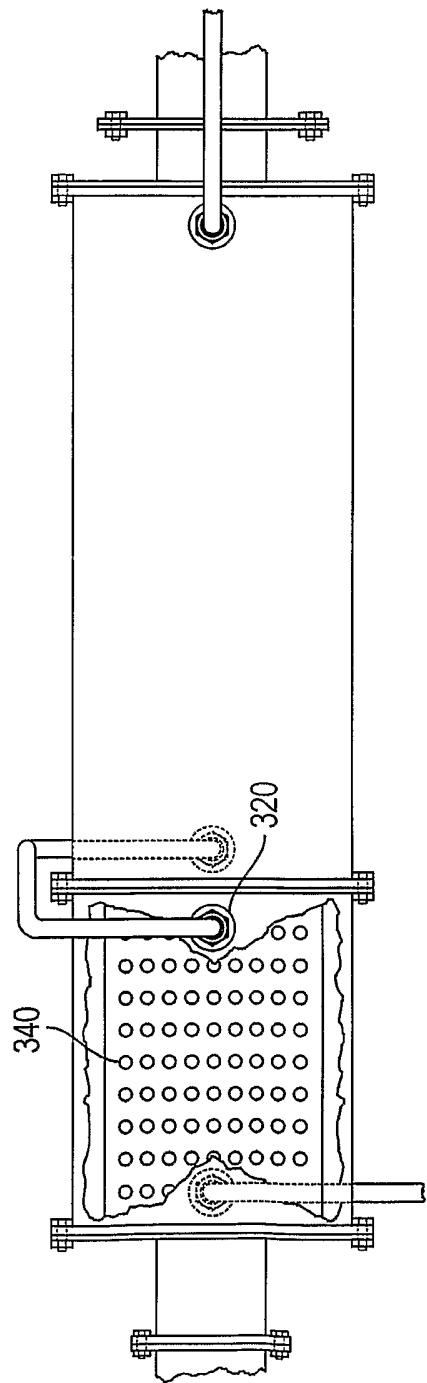
FIG. 4A
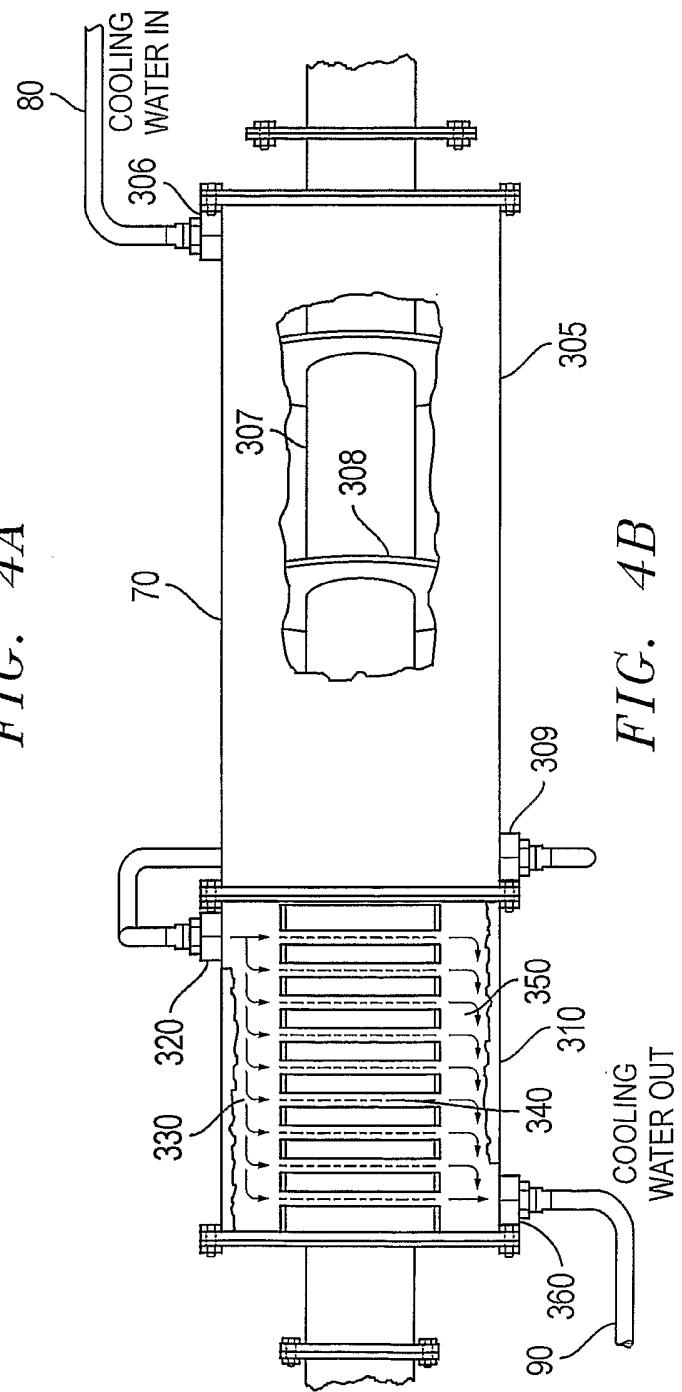
FIG. 4B
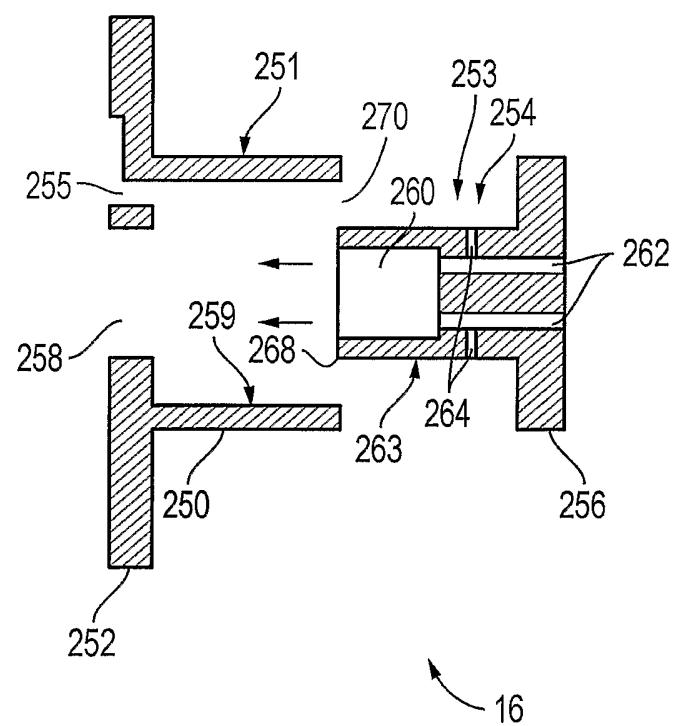
FIG. 5A

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FIG. 5B

FIG. 5C

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FIG. 5D
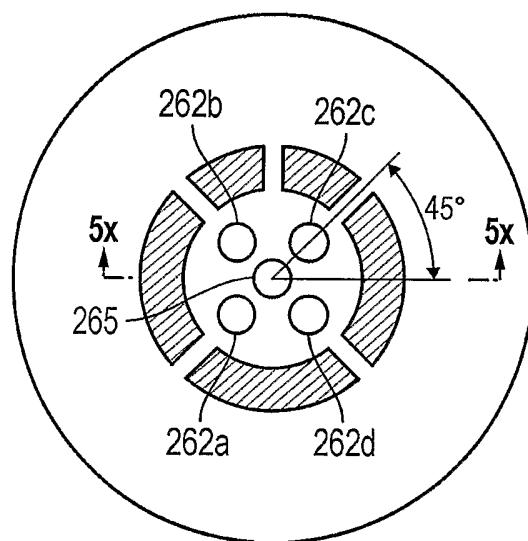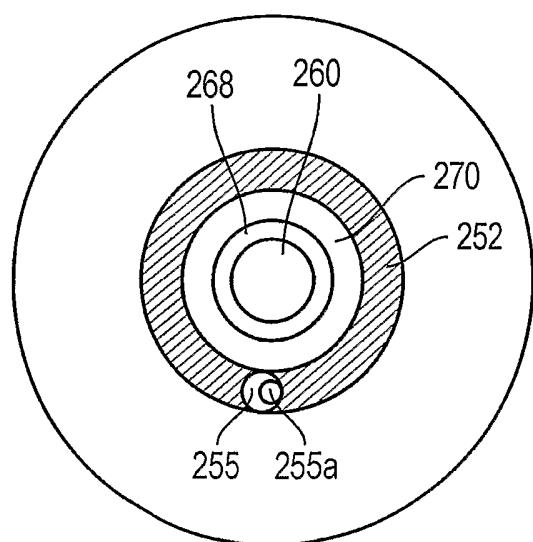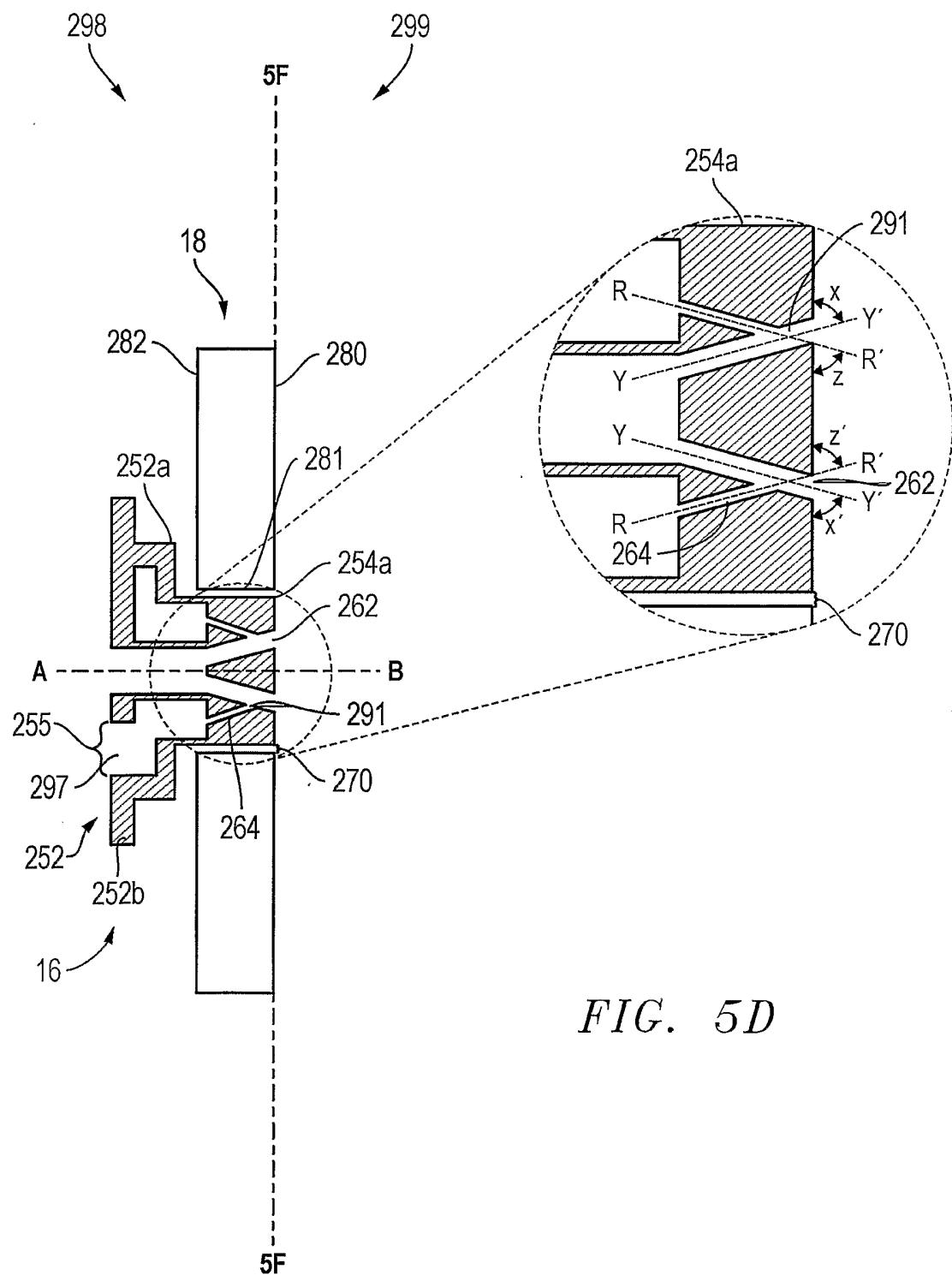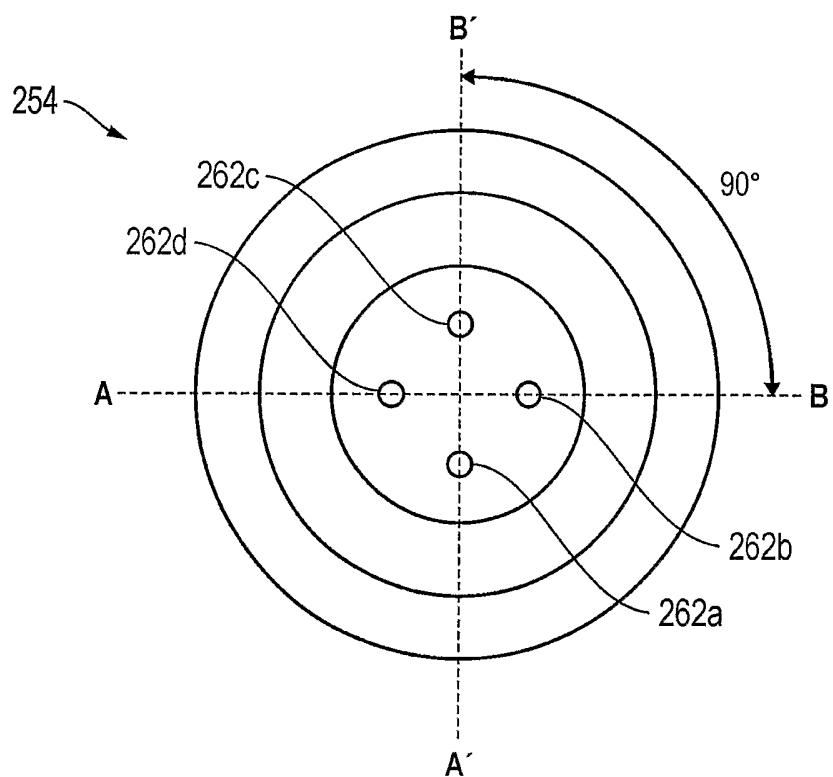
FIG. 5E

FIG. 5F

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FIG. 6B

FIG. 6A

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```
                                                    ┌─────────────────────┐
                                                    │   TEST CONTROLLER   │── 720
                                                    └─────────────────────┘
        ┌──────────┐                                          │
710 ──  │  SET UP  │ ◄─────────────┐                          ▼
        └──────────┘               │         ┌──────────────────────────────────────┐
             │                     │         │ USER INPUT:                           │
             ▼                     │         │ -AF ADJUSTMENT SETTING TIME           │
 ┌──────────────────────────────┐  │         │ -2-STEP AF/TIME CYCLE                 │
 │ -MANUAL CONTROL OF AIR PUMP  │  │         │ -1ST STAGE EXHAUST TEMPERATURE LIMIT  │
 │ -MASS/VOLUMETRIC AIR FLOW    │  │         │ -2ND STAGE EXHAUST TEMPERATURE LIMIT  │
 │ READOUT                      │  │         └──────────────────────────────────────┘
 └──────────────────────────────┘  │                          │
                                   │                          ▼
                    730 ─  ┌────────────────────────────────────────────────────┐
                           │ START-UP SEQUENCE                                  │
                           │ -READ MASS AIR FLOW SETPOINT FROM FILE             │
                           │ -READ AF SETPOINT                                  │
                           │ -READ NUMBER OF BURNERS TO ACTIVATE                │
                           │ -DETERMINE AND SET INITIAL FUEL FLOW OUTPUT        │
                           │ -INITIATE SPARK                                    │
                           │ -INITIATE AIR FLOW                                 │
                           │ -INITIATE FUEL FLOW                                │
                           └────────────────────────────────────────────────────┘
```

$AF_1 > AF_{ACT}$

$AF_1 < AF_{ACT}$

$AF_2 > AF_{ACT}$

$AF_2 < AF_{ACT}$

NO — BURNER LIT? — 740

YES

TERMINATE PROGRAM? — 750

YES — DETERMINE AF SETPOINT

TAKE DATA

INCREASE FUEL1 — YES

DECREASE FUEL1 — YES

INCREASE FUEL2 — YES

DECREASE FUEL2 — YES

760

SHUTDOWN SEQUENCE
-SHUT OFF FUEL
-SHUT OFF OIL
-COOL DOWN
-SHUT OFF AIR
-REPORT REASON FOR
TERMINATION OF PROGRAM

NO — SAFETY CHECK OK? — 770

780 — TAKE DATA? — WAIT FOR SETTING TIME

TEST TIME, MIN, MAX, AVG TO DISK

FIG. 7

FIG. 8

FIG. 9

FIG. 10

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FIG. 11

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FIG. 12
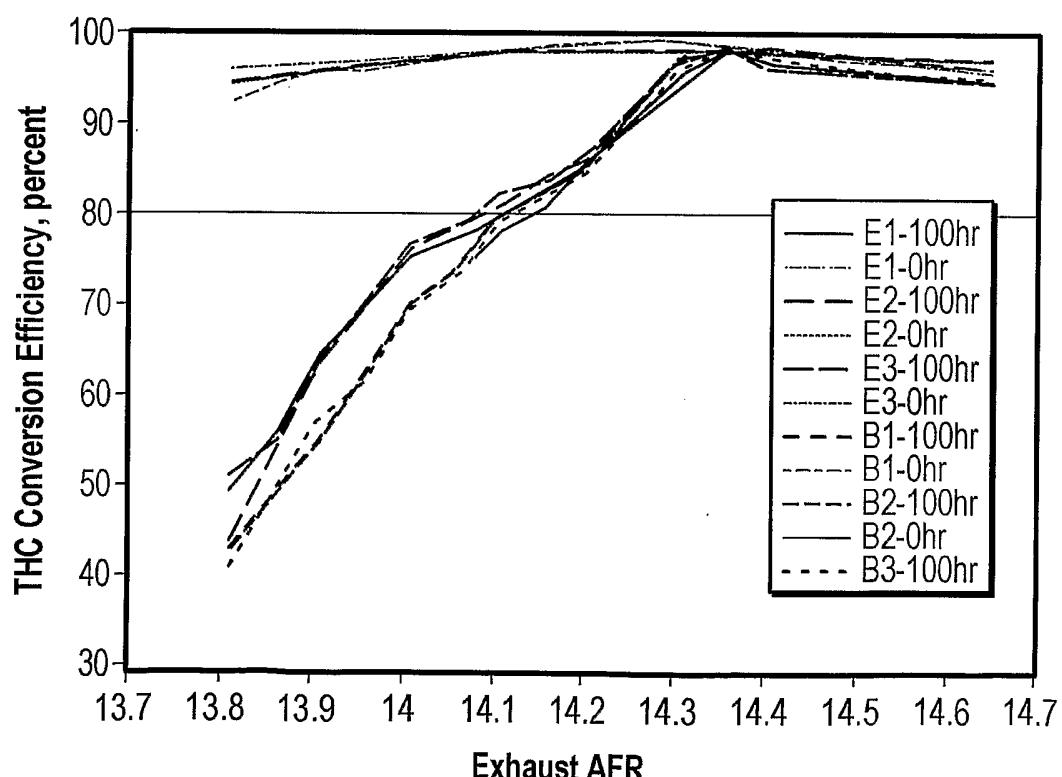
FIG. 13

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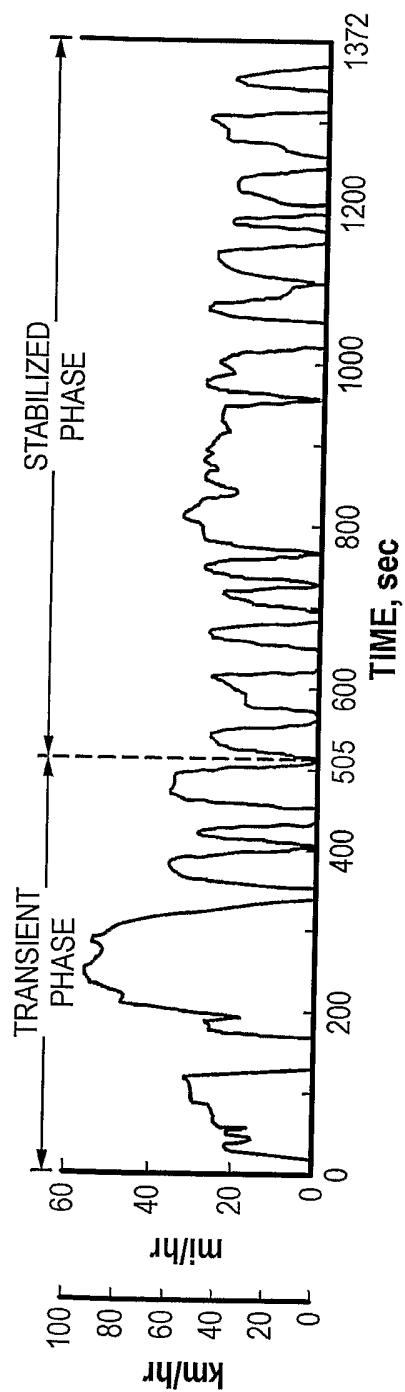
FIG. 14
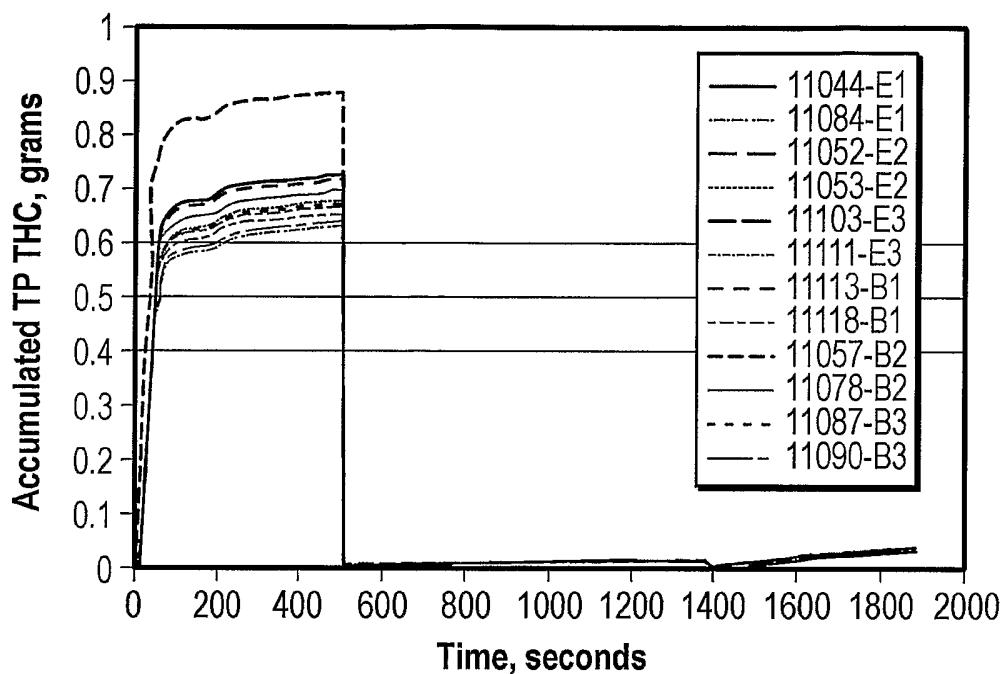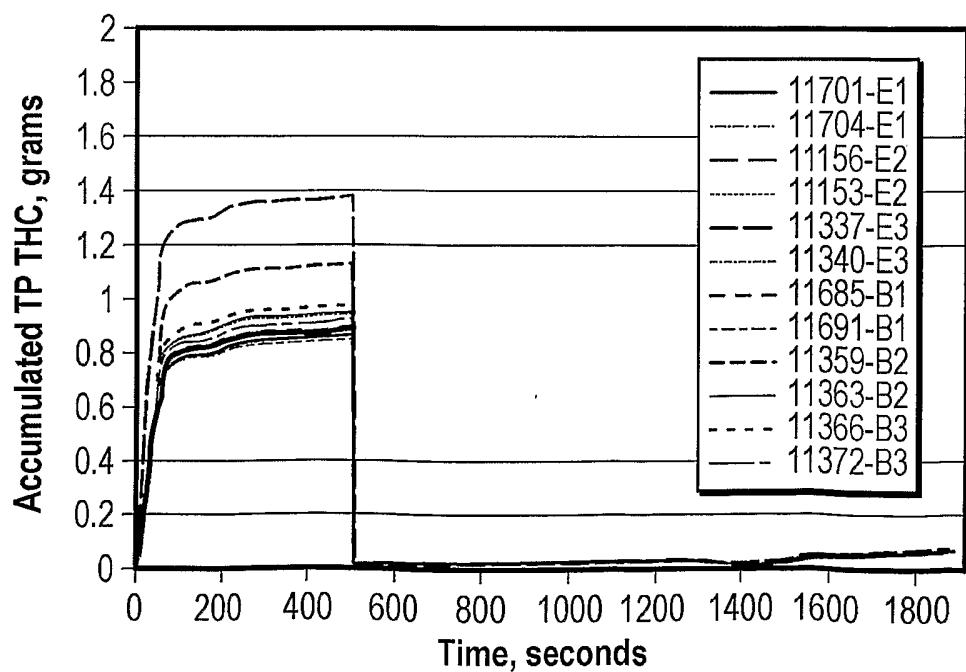
FIG. 15A

FIG. 15B

FIG. 15C

FIG. 15D

FIG. 16

FIG. 17

FIG. 18

| .... Cat Tin | ----- 0.5 | ---- 1.0 |
| ---- 1.5 | ------ cat out | —— Main UEGO |

FIG. 19A

| .... Cat Tin | ----- 0.5 | —— 1.0 |
| ---- 1.5 | ------ cat Tout | —— AF act |

FIG. 19B

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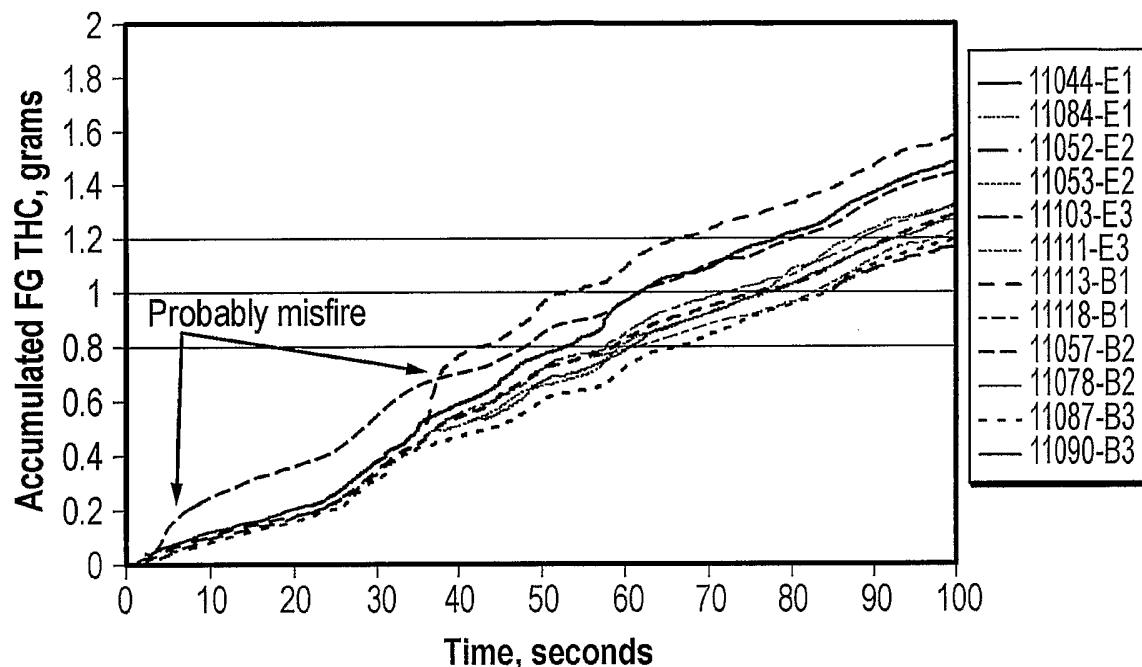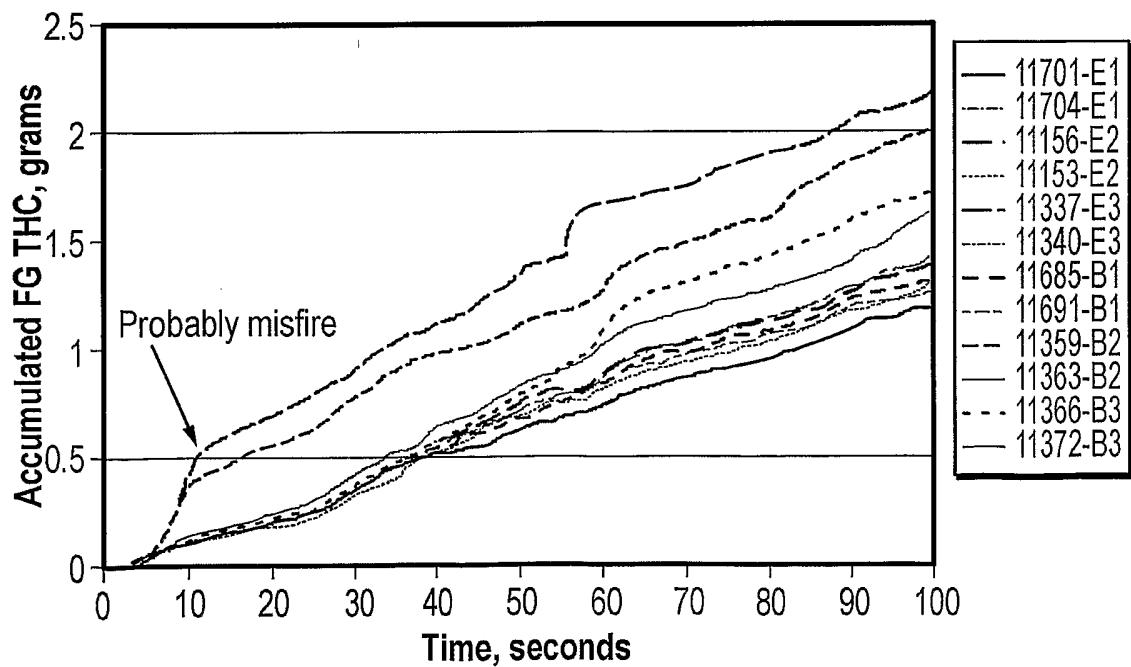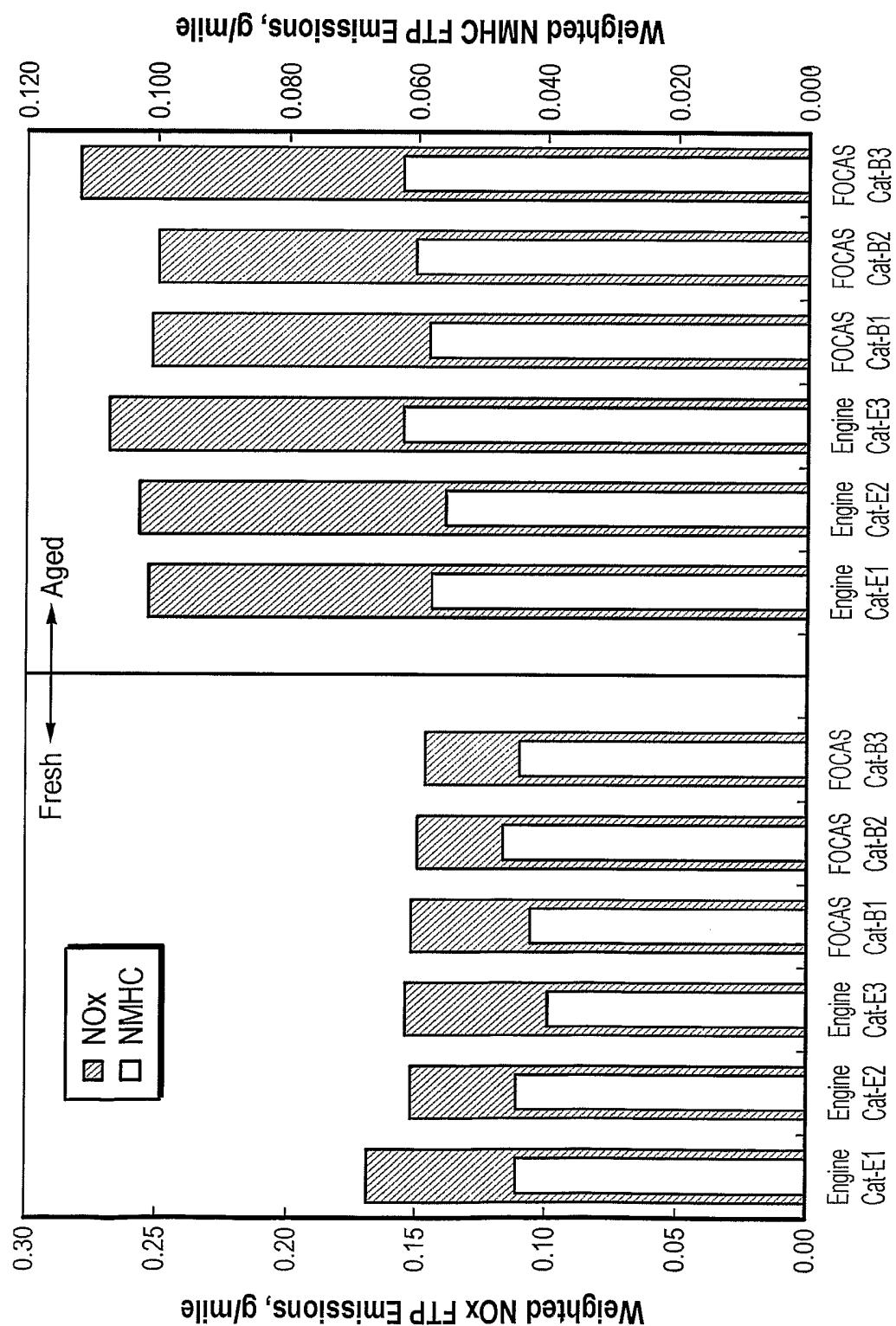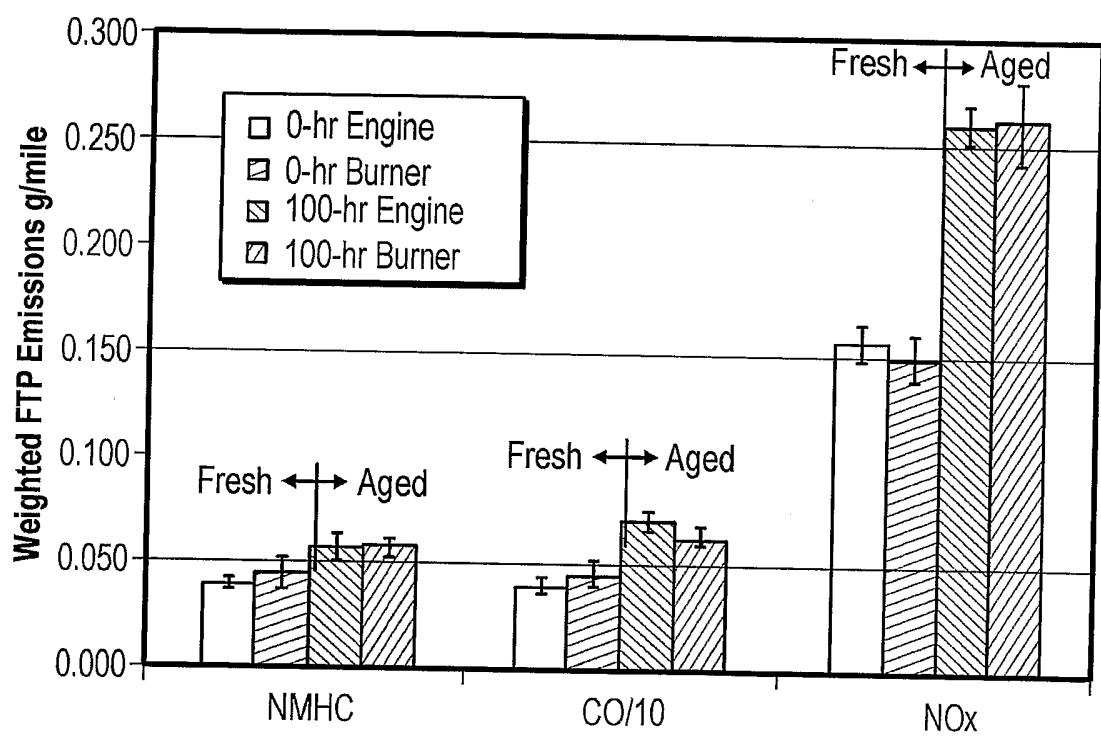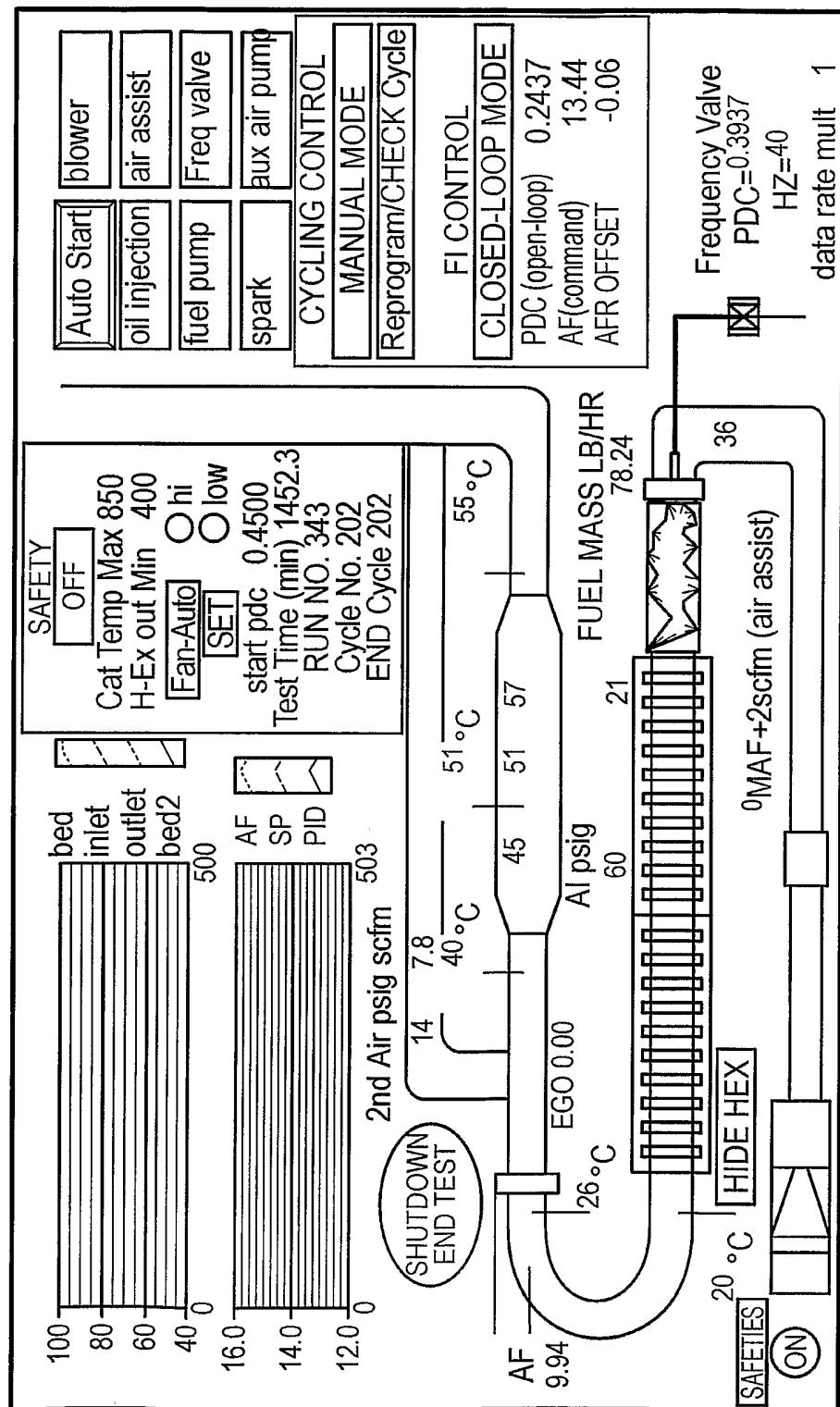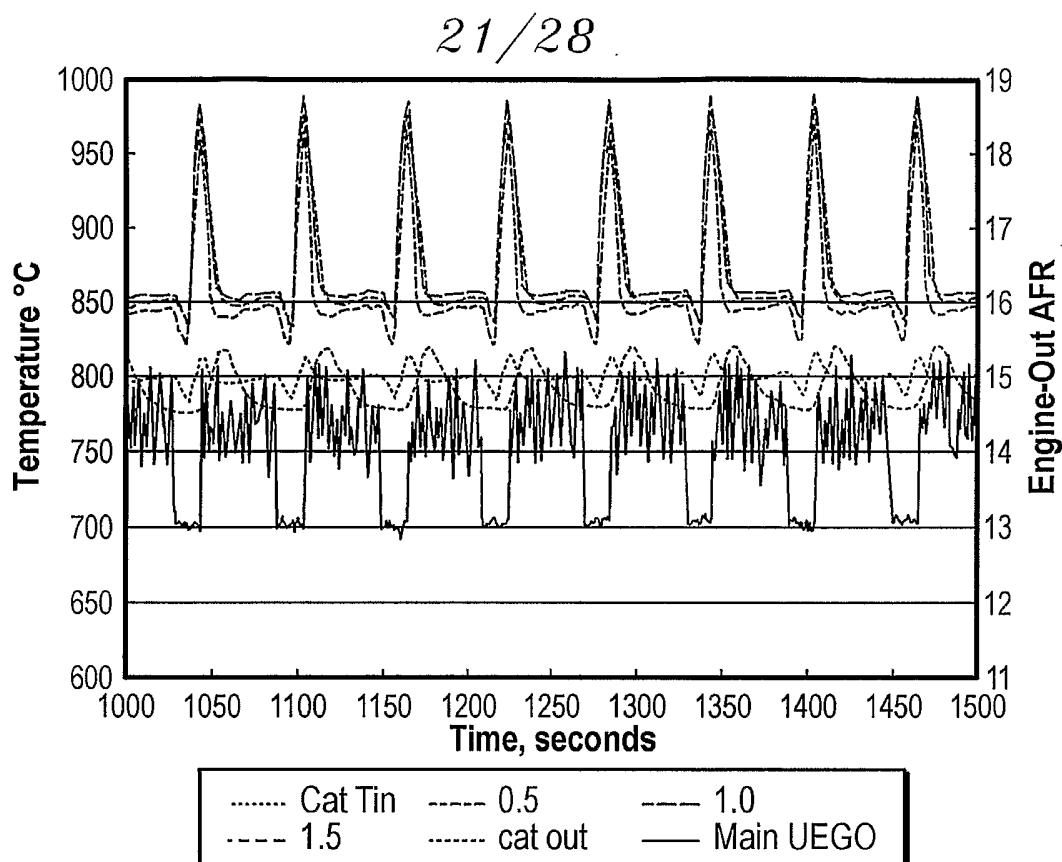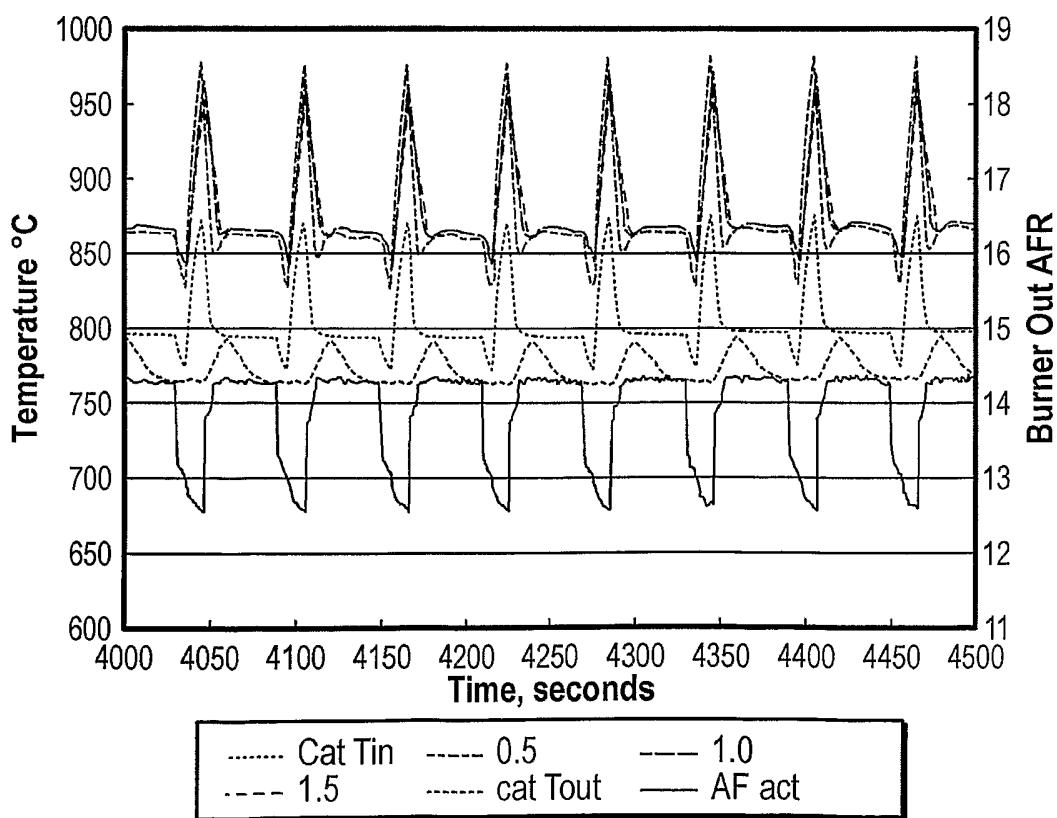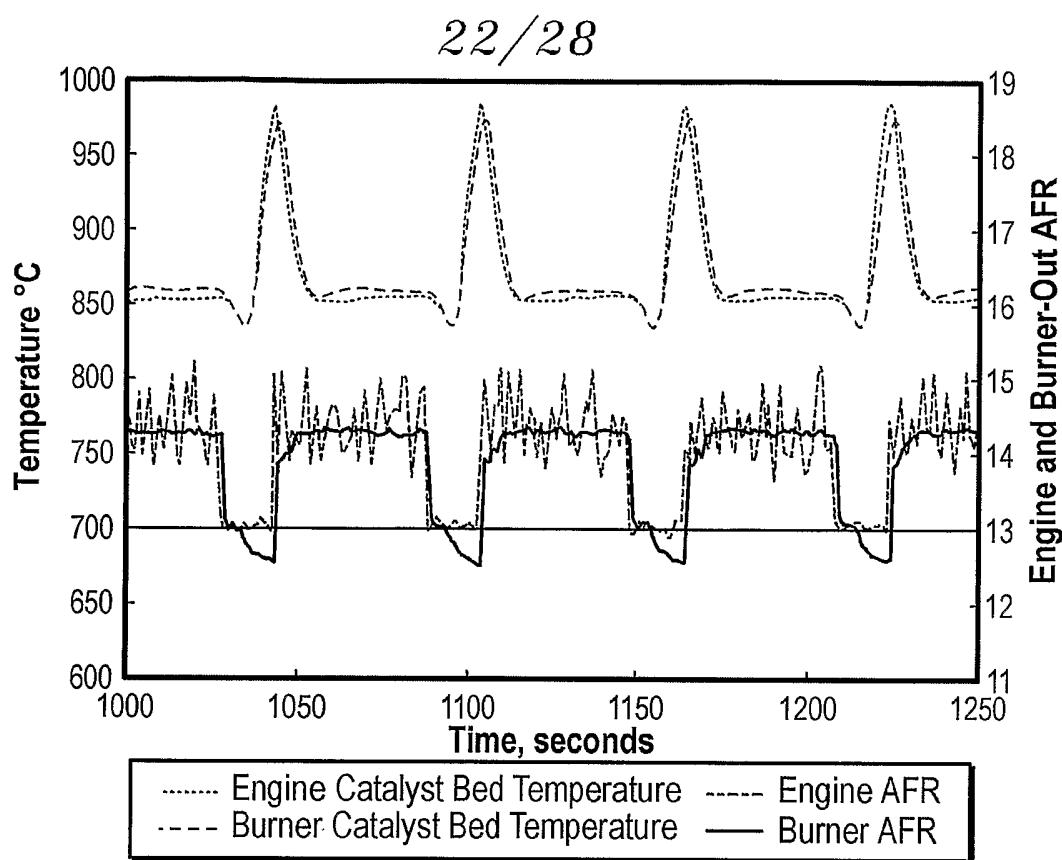
FIG. 19C

FIG. 19D

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Burner Wall

Swirl Plate

$$TAN\ \alpha = \frac{l_2}{l_1}$$

l_1

α

l_2
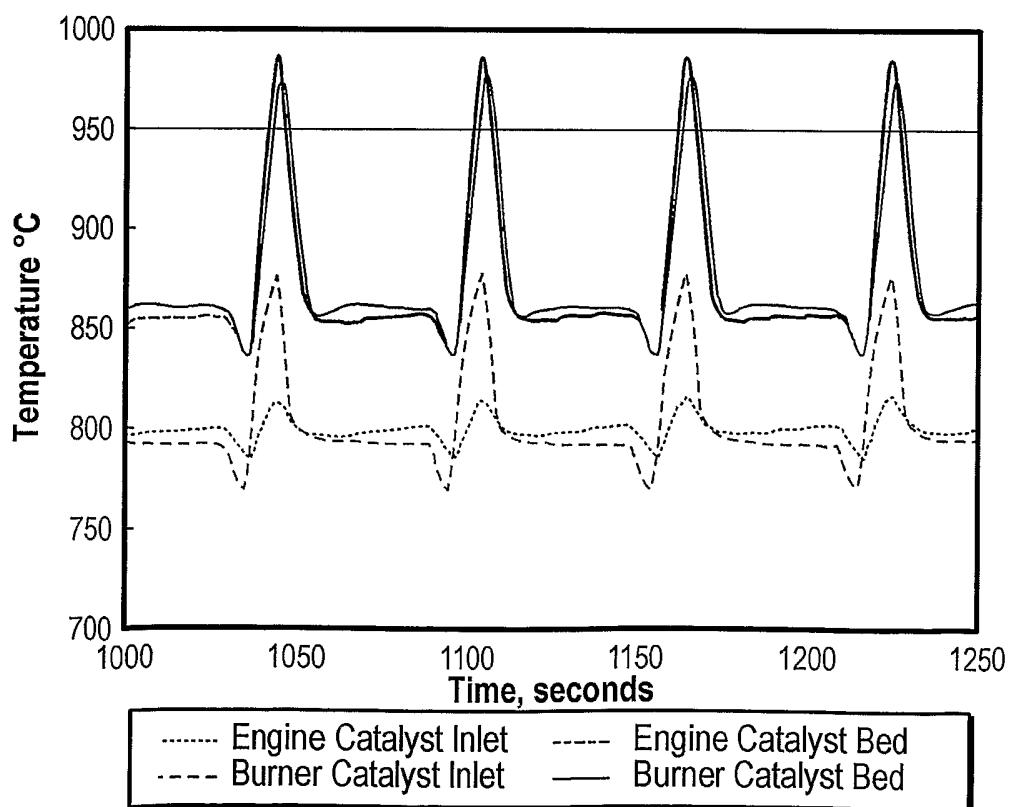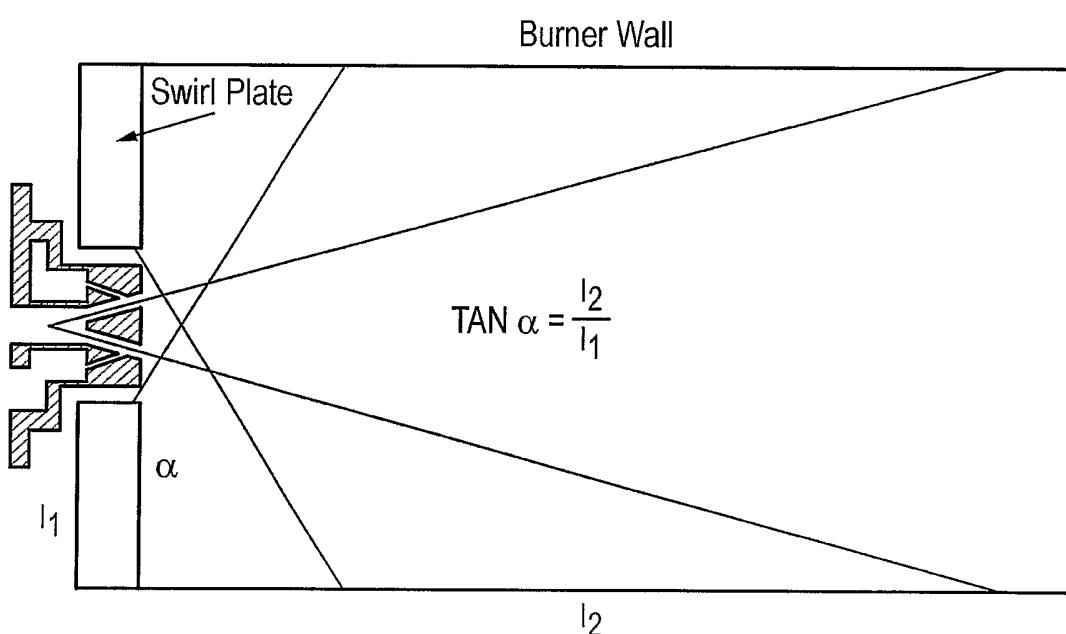
FIG. 20

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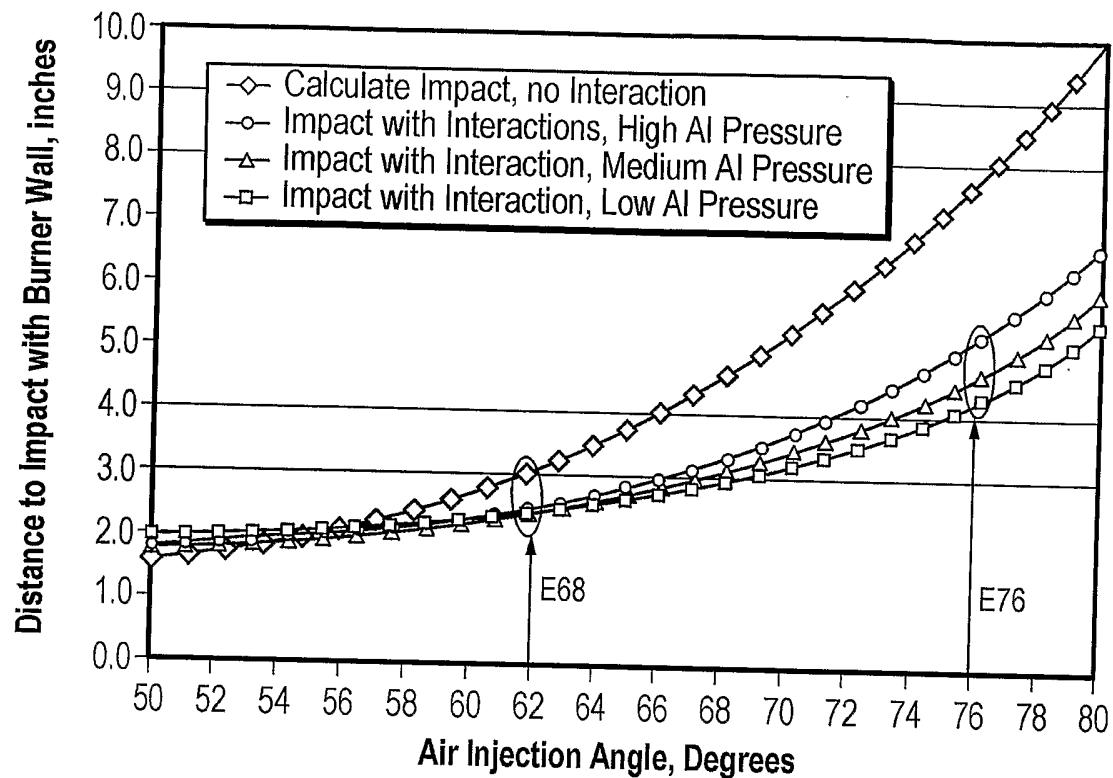
FIG. 21
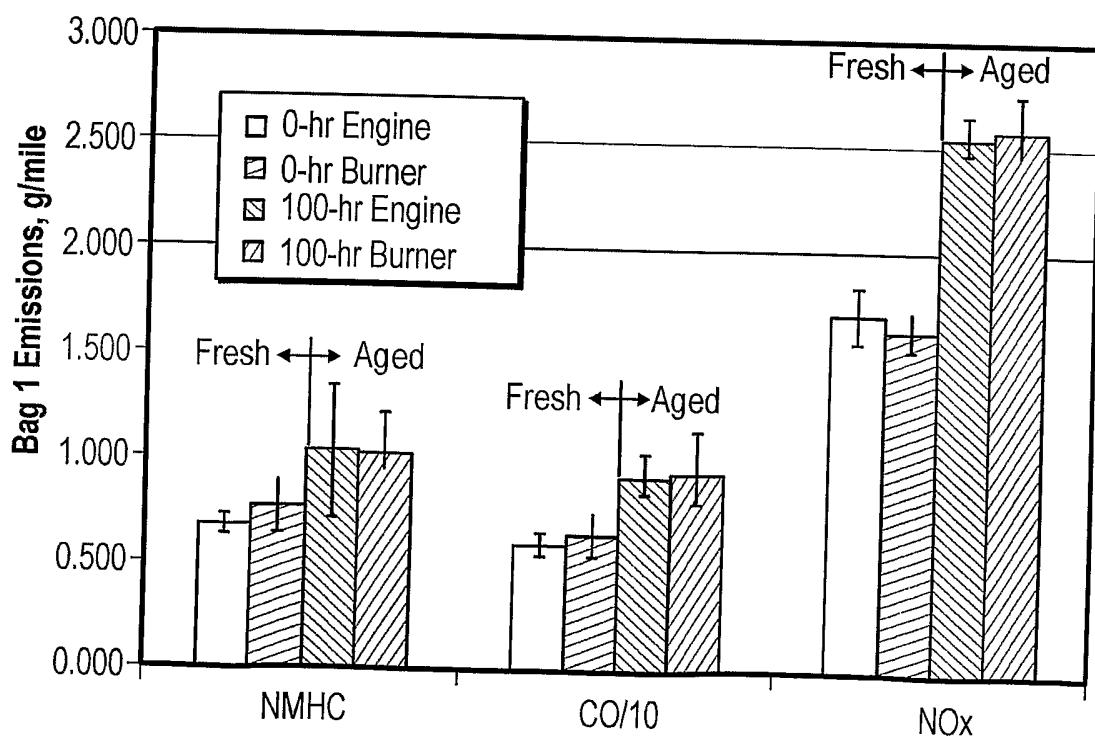
FIG. 22
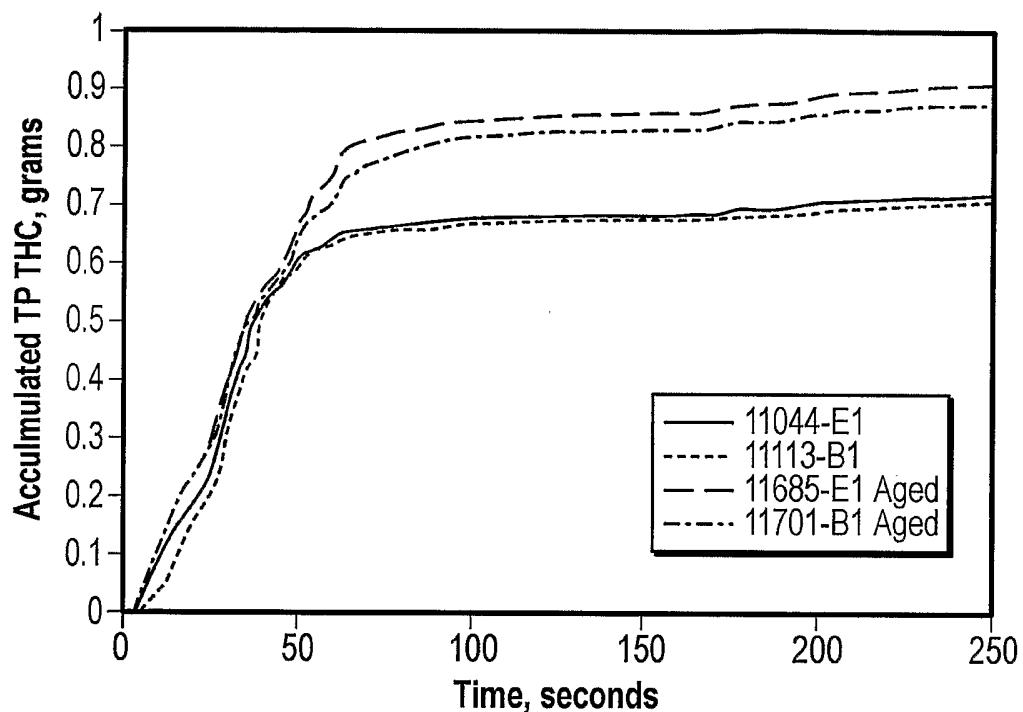
FIG. 23
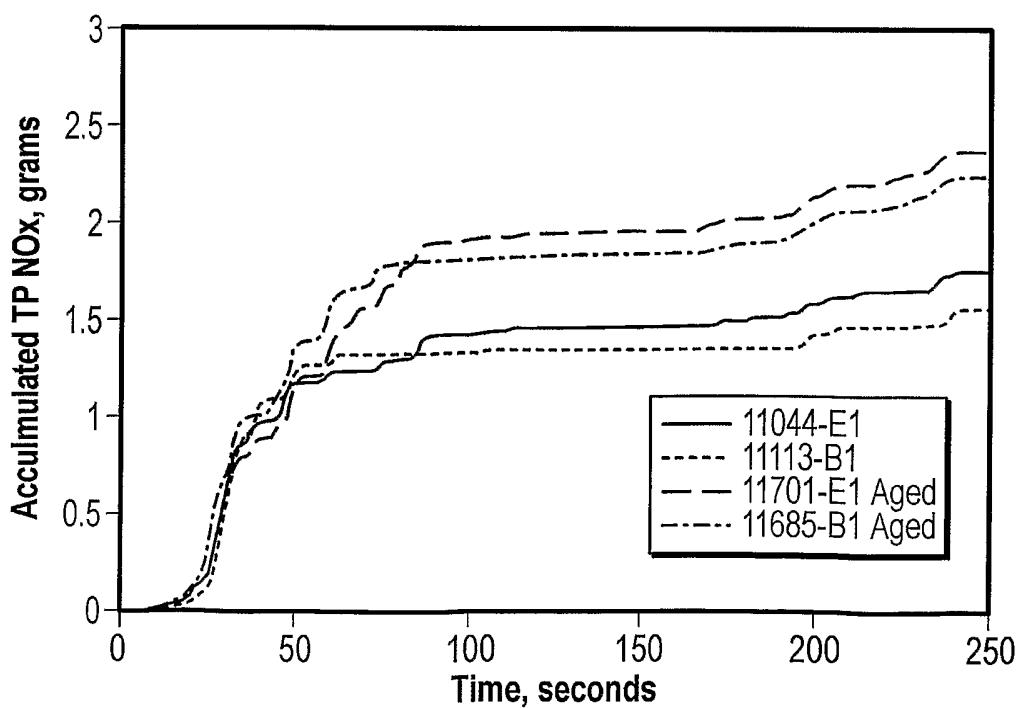
FIG. 24
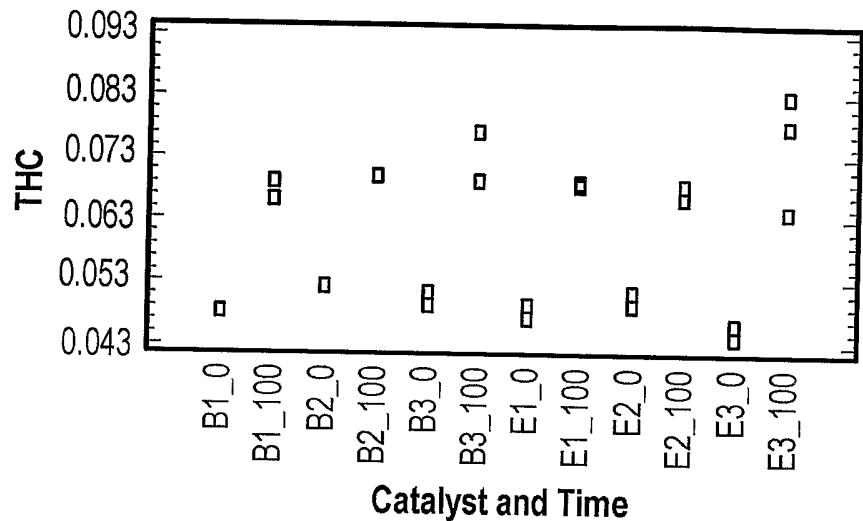
FIG. 25
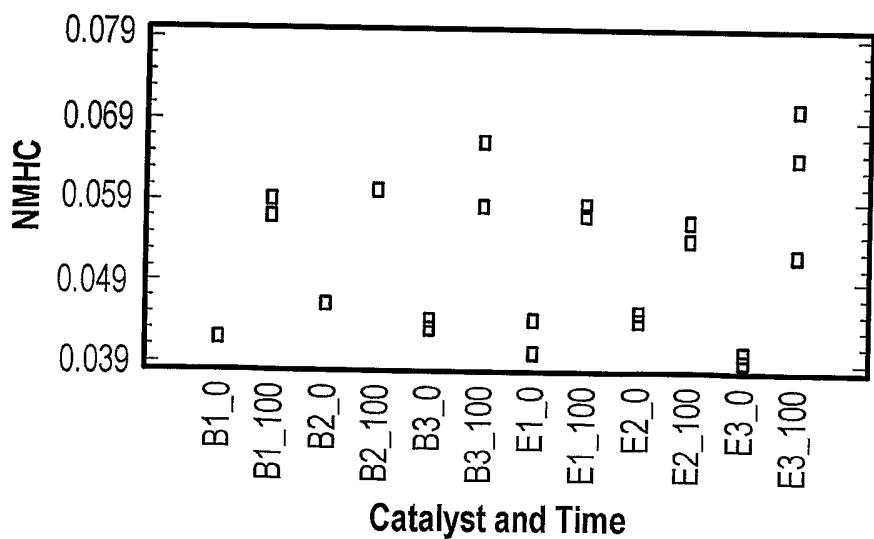
FIG. 26

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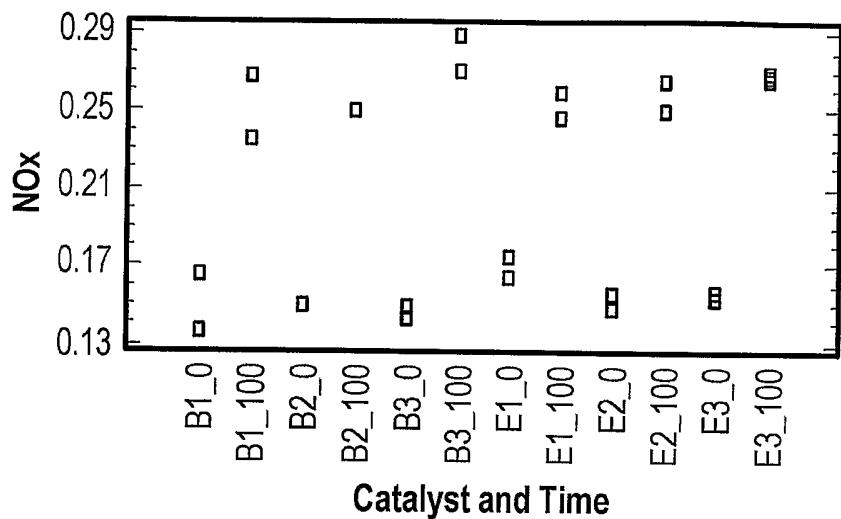
FIG. 27
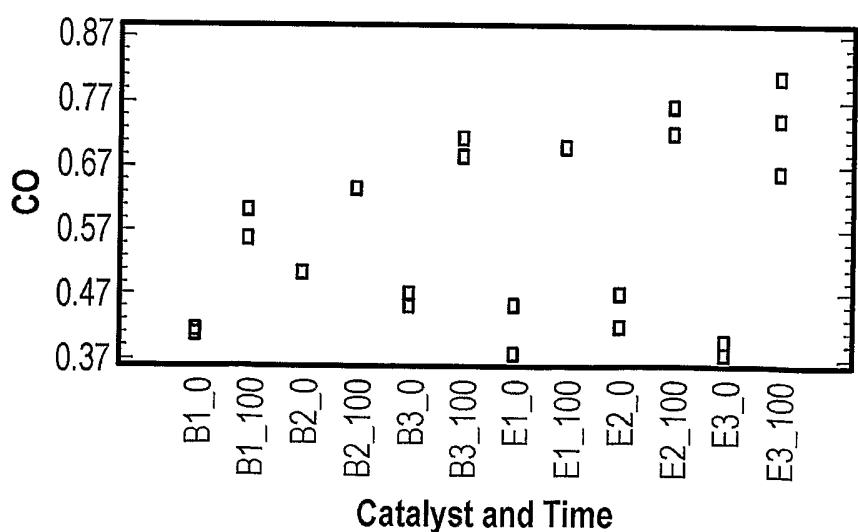
FIG. 28
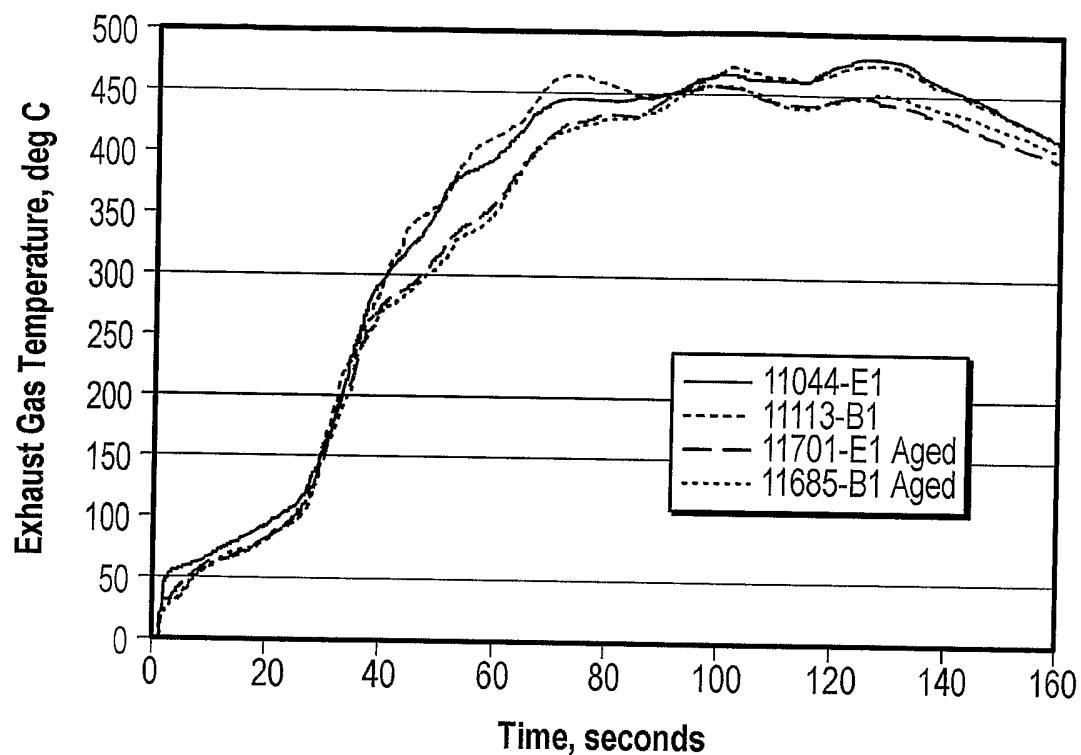
FIG. 29

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7)   :   F 23D 11/00,11/24, 11/36, 11/38; F23D 14/48, 14/84
US CL   :   431/1,9,10,181,187,350
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 431/1,9,10,181,187,350; 239/400

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,826,428 A (BLASCHKE) 27 October 1998 (27.10.1998), see the entire document.	1-3,29-31
X	US 5,339,630 A (PETTIT) 23 August 1994 (23.08.1994), see element 54.	1,23,29-31
Y		2,3,24,25
A	US 4,651,524 A (BRIGHTON) 24 March 1987 (24.03.1987), see the entire document.	1-3,26-31
A	US 6,071,113 A (TSUBOUCHI et al) 06 June 2000 (06.06.2000), see the entire document.	1-3,23-31
A	US 3,503,715 A (HAENSEL) 31 March 1970 (31.03.1970), see column 6, lines 12-33.	1
A	US 5,288,021 A (SOOD et al) 22 February 1994 (22.02.1994), see the entire document.	19-21
A	US 3,685,740 A (SHEPHERD) 22 August 1972 (22.08.1972), see the entire document.	19-21

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	
"E"	earlier application or patent published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	
"P"	document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 November 2002 (21.11.2002)	16 DEC 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer CARL D. PRICE Telephone No. 308-1148/0858

Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/24937

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claim Nos.: 4-18,22,32-43
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet(1)) (July 1998)