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(54) **Thermal enhancement.**

(57) Burner apparatus, comprising a tubular coolant jacket assembly, a tubular combustion chamber unit disposed within said coolant jacket assembly, and ignition zone structure at one end of said combustion chamber unit for flowing an ignited fuel-oxidant mixture into said combustion chamber unit, characterized in that said combustion chamber unit includes a monolithic tube of refractory material having an inner surface that defines a combustion zone, a reinforcing sleeve surrounding and extending the length of said tube having its outer surface being spaced less than one millimeter from the inner surface of said coolant jacket assembly in standby condition, providing residence time sufficient to complete combustion of the fuel-oxidant mixture within said combustion chamber unit such that the stream of combustion products discharged from the end of said combustion chamber unit remote from said ignition zone structure is essentially particulate free.

EP 0 200 195 A2

Thermal Enhancement

This invention relates to processes and apparatus for thermal treatment of subterranean geologic formations for enhancing recovery of geologic resources.

Thermal treatment of subterranean geologic formations is frequently useful in enhancing the recovery of geologic resources. For example, some petroleum materials, the so-called "heavy crudes", have viscosity and gravity characteristics such that those materials do not flow readily through the porous earth formations, and hence their recovery is exceedingly difficult. Recovery of such petroleum materials may be enhanced by flowing heated materials into the subterranean reservoir for viscosity reduction, mobility enhancement, and like purposes. In other recovery systems, thermal treatment apparatus may be used to promote chemical reactions, to initiate in situ combustion or retorting and the like. While thermal treatment systems have been proposed for downhole use, their operation has not been entirely satisfactory, due in part to the nature of the remote, relatively inaccessible and frequently harsh environment. Simple and sturdy constructions as well as simple and reliable controls are desirable for effective operation. It is also frequently desirable that the system not introduce either particulate material or excess oxygen into the geologic formation being treated.

In accordance with an aspect of the invention, there is provided thermal treatment apparatus for downhole deployment that includes a combustion stage with structure for intensely hot wall operation that defines a fuel-oxidant mixture combustion and retention zone, and ignition zone structure immediately upstream from the combustion zone in which a mixture of atomized liquid fuel and oxidant is ignited; together with a liquid injection stage immediately downstream from the combustion zone through which the stream of essentially particulate free, high temperature combustion products flows from the combustion zone and into which liquid to be vaporized is sprayed. The length of the chamber structure defining the hot wall combustion zone is preferably at least five times its width dimension and the zone is defined by a refractory wall whose surface is maintained at elevated temperature in excess of 1100°C in an arrangement in which the burning fuel-oxidant mixture is retained within the combustion zone until combustion is completed so that an essentially particulate free stream of combustion products is discharged from the combustion zone into the geologic formation to be treated. The liquid injection stage preferably has an elongated chamber of dimensions similar to and axially aligned with the hot wall combustion zone chamber.

A thermal enhancement process in accordance with the invention for recovering hydrocarbon materials and the like from subterranean geologic formations includes the steps of positioning combustion chamber structure downhole adjacent the geologic formation to be treated, flowing an oxidant liquid fuel mixture at or below stoichiometric ratio into an ignition zone of the combustion chamber structure and igniting the mixture, flowing the burning mixture into a combustion zone defined by wall structure surface maintained at a temperature in excess of 1100°C, retaining the burning oxidant-fuel mixture in the combustion zone sufficiently long to insure substantially complete combustion, and then discharging the resulting essentially particulate free, oxygen free product mixture into the subterranean formation to be treated. The invention provides reduced risk of plugging and/or degrading the natural porosity of the formation into which the mixture is discharged. In a preferred embodiment, the resulting stream of essentially particulate free combustion products is flowed through a vaporization zone while injecting water into the flowing combustion products stream, and a mixture of steam and combustion products including carbon dioxide is injected into an oil bearing formation for producing chemical and thermal stimulation interactions to enhance the speed and effectiveness of reservoir response.

In a particular embodiment, the thermal treatment apparatus includes an elongated cylindrical body about fifteen centimeters in outer diameter which is disposed downhole in a conventional oil well casing. A high temperature seal module is provided for deployment immediately above or below the thermal treatment apparatus for sealing the casing adjacent the geologic formation to be treated. That high temperature seal module includes annular die structure and metal sealing rings which are hydraulically extruded through the dies into the annulus between packer and the well casing. Other types of high temperature packers can also be used. The combustion and liquid injection stages are housed in axial alignment within a common elongated sleeve that fits within the well casing with an annular cooling jacket chamber that extends the length of both the combustion and liquid injection stages through which the liquid to be vaporized is flowed. The combustion stage includes structure that defines a fuel injection zone with an atomizing nozzle that introduces a well atomized spray of fuel into the ignition zone in a coaxial sheath of air, and a refractory lined combustion chamber whose surface is maintained at an intensely hot temperature. Air flowed into the ignition zone through swirl passage structure establishes a forced vortex flow which maximizes aerodynamic shear and fuel-air mixing rates in a highly stirred zone with moderate temperature rise that provides stable ignition and enhanced fuel evaporation in the toroidal vortex. The downstream boundary of the forced vortex ignition zone is defined by fixed flame stabilizer structure that includes convergent-divergent throat structure with an extensively and highly stirred reverse flow zone immediately downstream from the throat structure that maximizes the combustion rate in the upstream end of the hot wall combustion zone. Downstream from the reverse flow zone and continuing through the hot wall combustion zone is a region of free vortex plug flow in which combustion is completed. The system provides flame stabilization in two separate but interconnected regions, a first region serving as an ignition zone and the second region providing a hot gas recirculation pattern that provides flame stability in a zone of high swirl and intensely back mixed flow which promotes efficient combustion. The hot refractory wall surface maximizes combustion of any remaining unburned materials and the thermal lag of that surface provides a ready ignition source for relight and helps smooth out variations in heat release rate due to process fluctuations.

A particularly vulnerable component of burner systems is the combustion chamber liner which is subjected to severe thermal stresses both during operation of the system and start up and cool down sequences, and frequently fail. In accordance with another aspect of the invention the tubular combustion chamber unit housed within the tubular coolant jacket assembly includes a monolithic tube of refractory material whose inner surface defines the combustion zone. A metal reinforcing sleeve surrounds and extends the length of the refractory tube. The inner surface of the coolant jacket assembly and outer surface of the combustion chamber unit are dimensioned so that those surfaces are close to one another (less than one millimeter spacing) in standby or cool condition so that the combustion chamber unit has limited freedom to expand with that expansion being stabilized by the coolant jacket assembly so that compression forces in the refractory tube preferably do not exceed about one-half the safe compressive stress of the material; and the materials of the combustion chamber unit are selected to establish thermal gradient parameters across the combustion chamber unit to maintain the refractory tube in compression so that it is not subjected to tension forces that would produce fracturing of the refractory material during combustion system start up and cool down sequences, as well as during normal operation.

While a variety of materials may be used in the combustion chamber unit, silicon compounds are preferred refractory tube materials, and high temperature metal alloys such as 304 stainless steel, Hasteloy, and Incoloy are preferred for the reinforcing sleeve. Refractory bonding material between the reinforcing sleeve and the refractory tube provides a thermal transition region and the gradient of that region may be adjusted as desired, for example with the addition of thermally conductive particles in the bonding material. A thermal adjusting coating also may be applied to the outer surface of the metal sleeve.

In a particular embodiment designed for downhole deployment, the coolant jacket assembly is an elongated cylindrical structure about 15 centimeters in outer diameter and about 11 centimeters in inner diameter. The combustion chamber unit disposed within the coolant jacket assembly includes a tube of cast silicon carbide that defines a combustion chamber about 7 1/2 centimeters in diameter and about 92 centimeters in length. A stainless steel reinforcing sleeve has an outer diameter of slightly less than 11.5 centimeters so that there is an annular space of about 0.25 millimeter between the outer surface of the liner unit and the inner surface of the coolant jacket assembly. A transition region between the stainless steel sleeve and the silicon carbide tube is filled with an aluminum oxide bonding agent that has a substantially greater thermal gradient than either the silicon carbide tube or the stainless steel sleeve. In addition a thin coating of zirconia is provided on the outer surface of the metal reinforcing sleeve. The burner system includes ignition zone structure at one end of the combustion chamber unit for flowing an ignited fuel-oxidant mixture into the combustion chamber unit and a liquid injection stage immediately downstream from the combustion chamber unit through which a stream of essentially particulate free high temperature combustion products flows and into which liquid from the coolant jacket assembly is sprayed for vaporization.

The system provides a burner system that is capable of operation for extended periods of time on an unsupervised basis in remote and inaccessible environments while maintaining stability and with minimal degradation, the refractory tube being maintained in compression without subjecting other system components to excessive stress.

The downstream elongated liquid injection stage includes a tubular sleeve that supports an array of axially and circumferentially spaced spray nozzles through which water is injected at a controlled rate to generate steam and/or to control the temperature of the discharged mixture of combustion products and vaporized liquid.

Liquid fuels are efficiently burned in downhole environments with processes and apparatus in accordance with the invention with complete combustion so that the resulting stream of combustion products is essentially particulate free. The system is simple and sturdy in construction, is efficient and provides reliable operation over a range of operating conditions.

The burner apparatus that is the subject of claim 1 includes a tubular combustion chamber housed within a tubular coolant jacket assembly in an arrangement which controls and limits radial expansion of the refractory combustion chamber liner such that the burner system can be operated at high temperatures (in the order of 1400 °C, for example) without subjecting the combustion liner to excessive compression forces at its inner surface which would cause a spalling type of failure.

In that burner apparatus, the inner surfaces of the combustion chamber unit is spaced from the inner surface of a coolant jacket assembly such that an air gap is provided in standby condition between the inner surface of the coolant jacket assembly and the outer surface of the combustion chamber unit.

Thermal expansion of the monolithic tube during burner apparatus operation causes the outer surface of the combustion chamber unit to engage the inner surface of the coolant jacket assembly such that the reinforcing sleeve and the containing action of the coolant jacket assembly maintains the refractory material in compression during burner apparatus operation.

There is no suggestion in the prior art of the apparatus as defined in claim 1, namely:

a balanced combustion burner chamber system which allows moderate but not excessive expansion of the refractory tube while not subjecting that tube to either excessive compression or expansion stresses at burner operating conditions.

The following prior art has become known:

US-A-4 078 613:

A downhole recovery system for burning a mixture of hydrogen and oxygen to produce steam, carbon dioxide and hydrogen.

The system in accordance with the invention, in contrast, provides a system in which a mixture of atomized liquid fuel and air is completely combusted in an elongated hot wall combustion zone; together with a water injection stage immediately downstream from the combustion zone through which essentially particulate free high temperature combustion products flow and into which water is sprayed. The resulting mixture of steam and particulate free combustion products is injected into an (oil) formation.

US-A-3 456 721:

A downhole burner with a perforated refractory lined combustion chamber through which water is injected into quench zone 10 immediately downstream from burner 5. The single drawing figure shows water injection ports upstream from the burner orifice so that water is injected directly against the burner housing.

Thus, this burner does not have an elongated hot wall combustion zone for the substantially complete combustion of the air fuel mixture.

US-A-3 982 591:

A system similar to that shown in **US-A-4 078 613** in which hydrogen and oxygen are fed into primary combustion zone 67 and water is sprayed through apertures 63.

The embodiment shown in Fig. 17 shows the water sprays directly impinging on the combustion process so that the process would tend to be quenched prior to complete combustion, which the resulting materials discharged through nozzle 49.

Prior art systems of the type discussed above for thermally enhancing the recovery of hydrocarbon materials from downhole geologic formations typically generated significant quantities of soot (particulates) which tended to clog geologic formations.

The system in accordance with the invention,

- in contrast with those prior art systems which resorted to catalysts or gaseous fuels,

provides a long, hot combustion chamber defined by a combustion liner of refractory material which defines a high temperature zone (maintained at temperatures in excess of 1100 °C) in a high pressure environment; combustion of the fuel is maximized by that long hot walled zone (even though the zone is at high pressure which produces poor fuel atomization) so that the resulting combustion product stream is essentially particulate free;

- downstream from the long hot combustion zone is a vaporization zone into which the particulate free combustion product stream flows directly (without a nozzle throat or other flow restriction) for vaporizing liquid injected thereinto.

Other features and advantages of the invention will be seen as the following description of particular embodimentsprogresses, in conjunction with the drawings, in which:

Fig. 1 is a diagram of a thermal recovery system in accordance with the invention;

Fig. 2 is an enlarged view of a portion of the injection well of Fig. 1;

Fig. 3 is a sectional view of the thermal stimulation unit taken along the line 3-3 of Fig. 2;

Fig. 4 is a sectional view, on an enlarged scale, of portions of the thermal stimulation unit taken along the line 4-4 of Fig. 3;

Figs. 5-9 are sectional views taken along the lines 5-5, 6-6, 7-7, 8-8, and 9-9 respectively of Fig. 4;

Fig. 10 is a sectional view taken along the line 10-10 of Fig. 2;

Fig. 11 is a sectional view of portions of another thermal stimulation unit in accordance with the invention;

Figs. 12 and 13 are sectional views taken along the lines 12-12 and 13-13 respectively of Fig. 11;

Fig. 14 is an enlarged sectional view of a portion of the unit shown in Fig. 11; and

Fig. 15 is a diagram indicating aerodynamic flow conditions in the thermal stimulation units shown in Figs. 4 and 11.

Description of Particular Embodiments

The system shown in Fig. 1 includes an injection well 10 that extends downwardly from the surface 12 of the ground to an oil reservoir 14 or other similar subsurface geologic formation. A producing well 16 extends upwardly from reservoir 14 to processing equipment that includes such apparatus as oil/water separation unit 20, and flotation separation unit 22. Steam generator support equipment includes air compressor 24 and fuel tank 26. Supplies including liquid fuel (such as No. 2 fuel oil, No. 6 fuel oil, or preprocessed crude oil), air, and water are fed from the surface equipment through injection well 10 to thermal stimulation system 30 at the base of well 10. Thermal stimulation products including steam and CO_2 produced by system 30 are released into reservoir 14, and stimulate flow of hydrocarbon materials from reservoir 14 through producing well 16 to surface treatment equipment 20, 22 for pumping to a refinery over lines 28.

Further details of the downhole thermal stimulation system 30 may be seen with reference to Fig. 2. That stimulation system is supported with a 17 3/4 centimeters diameter steel casing 32 by a tubing string 34 and includes a conventional packer body 36, a conventional slip assembly 38, a high temperature sealing module 40 and a steam generation unit 50. The tubing string 34 includes jointed pipe sections 42 (air supply) and 44 (water supply); a small diameter continuous tubing fuel line 46, and a small diameter continuous tubing hydraulic fluid line 48 for the packer. Tubing lines 46 and 48 are strung along side the jointed pipe sections 42, 44 and restrained at regular intervals by tube clamps 52 that both support the continuous tubing lines 46, 48 and center the bundle within the casing 32. Slip assembly 38 and seal module 40 are hydraulically set. The high temperature seal module 40 includes a pair of dies through which metal sealing rings 54, 56 are hydraulically extruded into the annulus between packer 40 and the well casing 32. To set seal module 40, hydraulic fluid from the surface (at ~~15,000 psi~~ 1050 kp/cm^2) first causes the slips to deploy and then extrudes the sealing rings 54, 56. Further details of seal module 40 may be had with reference to copending PCT application Serial No. PCT/US81/00216 filed 23 FEB 1981, entitled PACKER which disclosure is incorporated herein by reference. The assembly is retrieved in conventional manner by pulling upward on the tubing string 34, thus causing the slips to release and the sealing rings to loosen.

Further details of the steam generator unit 50 may be had with reference to Figs. 3 and 4. That generator unit is secured to flanged nipple 60 which is attached to the lower end of packer module 40. The upper flange 62 of coupling 64 is secured to nipple 60 by bolts 66 which pass through bolt holes 68. In similar manner bolts 70 pass through bolt holes 72 in the lower flange 74 of adaptor 64 to secure the upper end of the steam generator unit 50 against flange 74.

That steam generator unit includes axially aligned combustion section 76 and vaporizer section 78. Combustor section 76 includes a tubular refractory lined combustion chamber 80 that has a length of about ninety centimeters and an internal diameter of about 7 1/2 centimeters. Vaporizer section 78 has an axially aligned tubular chamber 82 that is about 90 centimeters in length and has an inner diameter of about 11 1/2 centimeters. A series of circumferentially extending arrays of jet nozzles 84 extends axially along the length of vaporizer chamber 82, the number of nozzles 84 in each circumferential array being greatest at the inlet end of vaporizer chamber 82 and decreasing towards outlet port 86.

As indicated in Figs. 4 and 5, a number of passages extend through adaptor coupling 64, including fuel passage 100, electronics passage 102, two air passages 104A and 104B, and four water passages 106. Coupling 64 is bolted to nozzle housing 110, as indicated in Figs. 4 and 6, so that fuel passage 100 communicates with inclined groove 112 that extends to central chamber 114 in nozzle housing 110. Chamber 114 has an internal threaded bore 116 and an outlet port 120 which is surrounded by conical surface 118 on which atomizing nozzle unit 122 is seated. Nozzle unit 122 may be of the hollow cone type with a nominal spray angle of 75 degrees (measured at 40 psi), an orifice diameter of 1.6 millimeter and a core that imparts swirling motion to the liquid fuel. Nozzle 122 is threaded into adaptor 124 which has a central through passage 126 and which in turn is threaded into the bore of central chamber 114, so that the conical outer surface of the nozzle 122 is firmly seated at port 120.

As shown in Figs. 4 and 6, air passages 130A, 130B (which are aligned with corresponding passages 104A, 104B in adaptor 64) extend through nozzle housing 110 on either side of central chamber 114. The lower ends of passages 130 terminate at an annular recess 132 (Figs. 4 and 7) at the lower periphery of housing 110. Formed in the cylindrical wall of housing 110 above recess 132 are a stepped series of annular surfaces 134, 136, 138; and formed in the lower surface of nozzle housing 110 is a conical surface 140 that extends outwardly from port 120 to an annular ridge 142 in which are formed an array of eight slots 144.

Seated on surface 138 is the upper end of outer sleeve 150 (a stainless steel tube of .95 centimeter wall thickness, 200 centimeters in length, and 15 1/4 centimeters in diameter); and seated on surface 134 is an inner combustor housing sleeve 152 (a stainless steel tube of 0.6 centimeter wall thickness, 96 centimeters in length, and 12.7 centimeters in diameter) such that an elongated annular passage 154 defined between sleeves 150 and 152. Four water supply passages 156 (Fig. 6) in nozzle housing 110 extend from passage 106 in adaptor 64 (to the upper end of annular passage 154 at points immediately below surface 136.

The upper end of sleeve 152 has a counterbore 158 in which flame stabilizer throat member 160 is received. The planar upper surface 162 of throat 160 is seated on the planar end surface of ridge 142 and forms the lower boundary of air supply plenum 132. Air supplied through passages 104A, 104B and 130A, 130B to annular plenum 132 flows inwardly through swirl channels 144 into an ignition zone 164 bounded on its upper side by conical nozzle holder surface 140 and on its lower side by conical surface 166 of flame stabilizer member 160. Convergent surface 166 of throat member 160 extends to five centimeters diameter throat orifice 168 and divergent surface 170 defines an expansion transition to lined combustion chamber 80. Flame and temperature sensors monitor ignition zone 164 and transmit signals over conductors that extend through passages 128 and 102.

Received within combustor housing sleeve 152 and seated on the lower surface of throat member 160 is a --cast aluminum oxide (Al_2O_3) refractory sleeve 172 of of 0.95 centimeter thickness, and an array of arcuate aluminum oxide (Al_2O_3) refractory segments 174, each 0.95 centimeters in thickness and 120 degrees in angular extent. The inner surfaces of arcuate segments 174 define the inner wall of combustion chamber 80 as indicated in Fig. 8. Sleeve 172 and the array of arcuate segments 174 are secured within sleeve 152 by a transition ring 176 that is welded to the lower end of sleeve 152. Transition ring 176 has a cylindrical surface 178 of ten centimeters diameter and a lower surface 180 that diverges at an angle of 35 degrees to the system axis. Extending through ring 176 from chamber 154 to surface 180 are an array of eight jet spray passages 182, each 0.76 millimeter in diameter.

Welded in similar manner to the lower end of transition ring 176 is vaporizer chamber sleeve 184 (a stainless steel tube of 0.63 centimeter wall thickness, 96 centimeters in length, and 12.7 centimeters in diameter) which defines vaporization zone 82. A series of ten circumferential arrays 186 of jet nozzles 84 are secured in bores through the wall of sleeve 184, there being three circumferential arrays (186-1 - 3) of eight nozzles each (axially spaced about five centimeters apart) (Fig. 9), three circumferential arrays (186-4 - 6) of six nozzles each (axially spaced about five centimeters apart), and four circumferential arrays (186-7 - 10) of four nozzles each, (axially spaced about ten centimeters apart) along the axial length of vaporization zone 82.

Each jet nozzle 84 is of the hollow cone type and has an 0.76 millimeter diameter orifice. Spacer ring 188 is welded to the end surfaces of sleeves 150 and 184 and defines the lower end of annular water supply chamber 154. A cross-sectional view of vaporizer zone 82 is shown in Fig. 10.

Details of another thermal enhancement unit 50' may be had with reference to Figs. 11-14, in which elements corresponding to those of generator unit 50 are identified with a primed reference numeral. Unit 50' has tubular coupling adaptor 64' welded to end plate 200. The upper ends of outer sleeve 150' (a stainless steel tube of about 1 1/4 centimeter wall thickness, about fifteen centimeters in outer diameter, and 200 centimeters in length) and inner transition sleeve 202 (a stainless steel tube of about 0.6 centimeter wall thickness and about 12.5 centimeters in outer diameter) are also welded to end plate 200 so that an annular passage 204 is defined between those sleeves into which water is introduced from conduit 44'.

Welded to the lower end of transition sleeve 202 is flange 206 of ignition zone member 208. Carried by member 208 is adaptor 124' to which nozzle 122' is threadedly received and to which fuel oil is supplied through conduit 46'. Air flow through coupling adaptor 64' and port 210 in end plate 200 flows into the chamber 212. A portion of that air flows through passage 214 into the nozzle region for exit through orifice 120' in a coaxial sheath that surrounds the spray of atomized fuel droplets from nozzle 122' into the ignition zone 164'. Air also flows from chamber 212 through swirl passages 144' into the periphery of ignition zone 164'. Ignition zone member has a convergent surface 166' to a five centimeter diameter throat orifice 168' and a lower divergent surface 170'. Signals from temperature sensor 216 are transmitted over conductor 218 to surface located monitoring equipment. Welded to the lower side of flange 206 is the upper end of sleeve 152' (a stainless steel tube of about 0.63 centimeter wall thickness, 96 centimeters in length, and 12.7 centimeters in outer diameter). A helical channel 154', 7.6 centimeters in width and 0.15 centimeter deep is formed in its outer surface and provides with 0.63 centimeter wide helical ridge 220 a helical coolant flow path. Outer sleeve 150' is press or shrunk fitted over inner sleeve 152', and water flows from conduit 44' through a passage in end plate 200 to the annular passage 204 between sleeves 150' and 202 and through the helical path defined between the sleeves 150' and 152' along the length of the combustion zone 80'.

Welded to the lower end of sleeve 152' is transition ring 176', and seated on transition ring 176' is support ring 222. Housed within sleeve 152' and supported on support ring 222 is a refractory wall assembly 224 whose upper end 226 extends into the recess defined by outer surface 228 of ignition zone member 208. Assembly 224 includes stainless steel sleeve 230 (a tube of about 0.32 centimeter wall thickness and an outer diameter of about 11 centimeters) with a sprayed zirconia coating 232 on its outer surface; an inner sleeve 234 of cast high purity silicon carbide that has an inner surface 236 of 7.6 centimeters diameter and a 1 1/4 centimeter wall thickness; and an intermediate region 238 (about 0.32 centimeter in thickness) filled with cast aluminum oxide cement.

In the manufacture of liner assembly 224, sleeves 230 and 234 are concentrically located within a mold, and the refractory cement mixture (2200 parts Alumdun, 340 parts Melment plasticizer and 200 parts water) is poured into the space 238 while the mold is being vibrated so that the cement mixture fills the entire space. The assembly is dried at room temperature for 24 hours and then fired: 80°C for six hours; the temperature then increased at the rate of 24°C per hour to 496°C and held for four hours; and then cooled at a rate of 38°C per hour to room temperature. The cement securely bonds sleeves 230 and 234 together. The outer surface of sleeve 230 has a zirconia coating 232 (0.12 millimeter thickness) to provide an outer diameter of assembly 224 of about 11.38 centimeters.

Assembly 102 is then inserted into water jacket sleeve, there being an annular gap (see Fig. 14) of about 0.25 millimeter between the outer surface 122 of the liner unit and the inner surface 124 of the coolant jacket structure at ambient temperature.

Welded to the lower surface of transition ring 176' is sleeve 184' (a length of about 84 centimeters) that carries an array of spray nozzles 84'. Spacer ring 188' is welded to the lower ends of sleeves 150' and 184' and defines the lower end of annular water chamber 154', as well as outlet port 86'.

In use, steam generation system 30 is secured to tubing string 34 and lowered into the bore hole casing 32. After the steam generation system 30 is positioned in the bore hole adjacent the subterranean formation to be treated, as indicated in Figs. 1 and 2, packer slips 38 and seal 40 are hydraulically set, as indicated above, to provide a sealed pressure zone in communication with reservoir 14 in which system 30 is disposed. Liquid fuel is then flowed through line 46 (46') to nozzle 122 (122') for atomization and spraying into ignition zone 164 (164') as indicated in Fig. 15. Simultaneously air is supplied in stoichiometric ratio through passages 104 and 130 (port 210) to annular plenum 132 (chamber 212) and flows through swirl passages 144 (144') into ignition zone 164 (164') to form a forced vortex flow 250, and through port 214 into nozzle chamber for flow through orifice 120 (120') in a sheath 252 about the jet 254 of atomized fuel droplets from nozzle 122 (122'). Fuel ignition is by means of a hypergolic liquid (for example, triethylborane) flowed through fuel line 46 (46') in advance of the liquid fuel. The hypergolic liquid ignites in ignition zone 164 (164') in the presence of the sheath and swirl air flows and ignites the fuel-air mixture.

As the ignited fuel-air mixture burns, it flows through throat 168 (168') into highly stirred reverse flow zone 256 (at the upper end of refractory liner sleeve 172 (232)) which maximizes the combustion rate at the upper end of combustion zone 80 and then flows downstream from reverse flow zone 256 through zone 258 of free vortex plug flow in which combustion is completed.

As combustion commences, the temperature of surface 236 of the monolithic silicon carbide tube 234 increases, producing both axial and radial expansion of liner unit 224 until outer surface 240 of liner unit 224 seats against inner surface 242 of the coolant jacket assembly. The expanding silicon carbide is in compression and those compressive forces are stabilized at about one-half the safe compression stress of tube 234 by the containing action of the coolant jacket assembly. With stoichiometric ratio of air and No. 2 fuel oil, the combustion process temperature in zone 80' is in the order of 2040°C and the temperature of surface 236 of the silicon carbide liner is in the order of 1425°C. At a five million BTU per hour firing rate a coolant flow rate of thirty liters per minute is employed maintaining the temperature of the inner surface 242 of the water jacket in the order of 205°C or less. With the liner unit 224 stabilized by the coolant jacket, a thermal gradient, diagrammatically indicated in Fig. 14, is established across the liner components, the thermal gradient for coating material 232 being about twice that of bonding material 238, so that major temperature drops are taken across the aluminum oxide bonding material 238 and the thin zirconia layer 232. When combustion is terminated, silicon carbide sleeve 234 remains in compression as the system cools down so that it is not subjected to tension forces which would produce fracturing of the refractory material. This liner unit provides a physically stable combustion chamber surface 236 that provides an elongated high temperature wall combustion zone 80' in which stoichiometric air-fuel mixtures are completely burned so that the combustion product streams from combustion zone 80' are essentially particulate free and oxygen free and that may be repeatedly cycled through burner operation (start up and cool down) cycles.

The water flow through coolant jacket passage 154 limits the temperature rise of the refractory liner assembly with the thermal gradient being adjusted by material selection including those of coating 232 and bonding agent 238. The coolant water discharged from the combustion chamber coolant jacket flows into the vaporization zone channel and is sprayed in jets 260 through nozzles 84 into stream of combustion products in vaporization zone 82 (Figs. 10 and 15) and flashed to steam with the resulting mixture of steam and combustion products being discharged through outlet port 86 (86') for flow into the oil reservoir 14.

A range of characteristics of this steam generator system are set out in the following table:

	Injection Pressure		
	70 kp/cm ~~1000 psi~~	140 kp/cm ~~2000 psi~~	210 kp/cm² ~~3000 psi~~
Maximum Firing Rate, BTU*/hr	10 x 10^6	20 x 10^6	20 x 10^6
Steam output, kg ~~lbs~~/hr	4029 ~~8874~~	8074 ~~17,748~~	8074 ~~17,748~~
Required Air Flow, kg ~~lb~~/hr	3436 ~~7569~~	6873 ~~15,138~~	6873 ~~15,138~~
Required Water Flow, kg ~~lb~~/hr	3681 ~~8107~~	7361 ~~16,214~~	7361 ~~16,214~~
Required Fuel Flow, kg ~~lb~~/hr (Steam Generator)	230 ~~506~~	459 ~~1,012~~	459 ~~1,012~~

The system delivers 80 percent quality steam at reservoir pressures of up to 210 kp/cm² ~~3000 pounds per square inch~~ in quantities of up to 223 000 kg ~~1400 barrels~~ per day.

In one test run of the system shown in Figs. 11-13 of 80 hours duration at firing rates from 1 - 5 million BTU* per hour, using a Delavan Type A hollow cone pressure atomizing 80 degree 54 l ~~12 gallon~~ per hour nozzle, No. 2 fuel oil and air at stoichiometric ratio were flowed through the system with steam generation at pressures of 7 - 35 kp/cm² ~~100-500 psig~~. In another test run at atmospheric pressure with emulsified No. 6 fuel oil using a Delavan Type SNA air atomizing nozzle and stoichiometric air-fuel ratios the system operated at firing rates of 128,000 - 180,000 BTU* per hour. In each run the output stream from the system contained

* = 0,454 kg

less than 1/2 percent oxygen and was essentially particulate free (on the average, the output streams contained less than five parts per million particles greater than two microns in size).

Improved downhole thermal treatment processes and apparatus of the invention are capable of prolonged operation over a wide range of firing rates and reservoir pressures; the apparatus is of compact construction and suitable for use in connection with conventional oil field equipment; and the invention offers significant time and cost savings over surface generated steam for heavy oil recovery from deep reservoirs as well as other processes for recovery of resources from subterranean geologic formations.

While particular embodiments of the invention have been shown and described, various modifications will be apparent to those skilled in the art, and therefore it is not intended that the invention be limited to the disclosed embodiments or to details thereof, and departures may be made therefrom within the spirit and scope of the invention.

What is claimed is:

1. Burner apparatus, comprising
- a tubular coolant jacket assembly (150', 202),
- a tubular combustion chamber unit (224)
  - disposed within said coolant jacket assembly (150', 202), and ignition zone structure (164')
  - at one end of said combustion chamber unit (224)
  - for flowing an ignited fuel-oxidant mixture into said combustion chamber unit (224),

c h a r a c t e r i z e d in that
- said combustion chamber unit (224)
  - includes
  - a monolithic tube (234) of refractory material
    - having an inner surface (236) that defines a combustion zone,
  - a reinforcing sleeve (230)
    - surrounding and extending the length of said tube (234),
  - having its outer surface (240) being spaced (Fig. 14) less than one millimeter from the inner surface (242) of said coolant jacket assembly (150', 202) in standby condition,
  - providing residence time sufficient to complete combustion of the fuel-oxidant mixture within said combustion chamber unit (224)
    - such that the stream of combustion products discharged from the end of said combustion chamber unit (224) remote from said ignition zone structure (164') is essentially particulate free

(Figs. 11 - 14).

2. Burner of claim 2,

c h a r a c t e r i z e d in that
- the material and the dimension parameters of said combustion chamber unit (224)
  - are such that said refractory material (224) is in compression throughout system operation including both start up and cool down sequences.

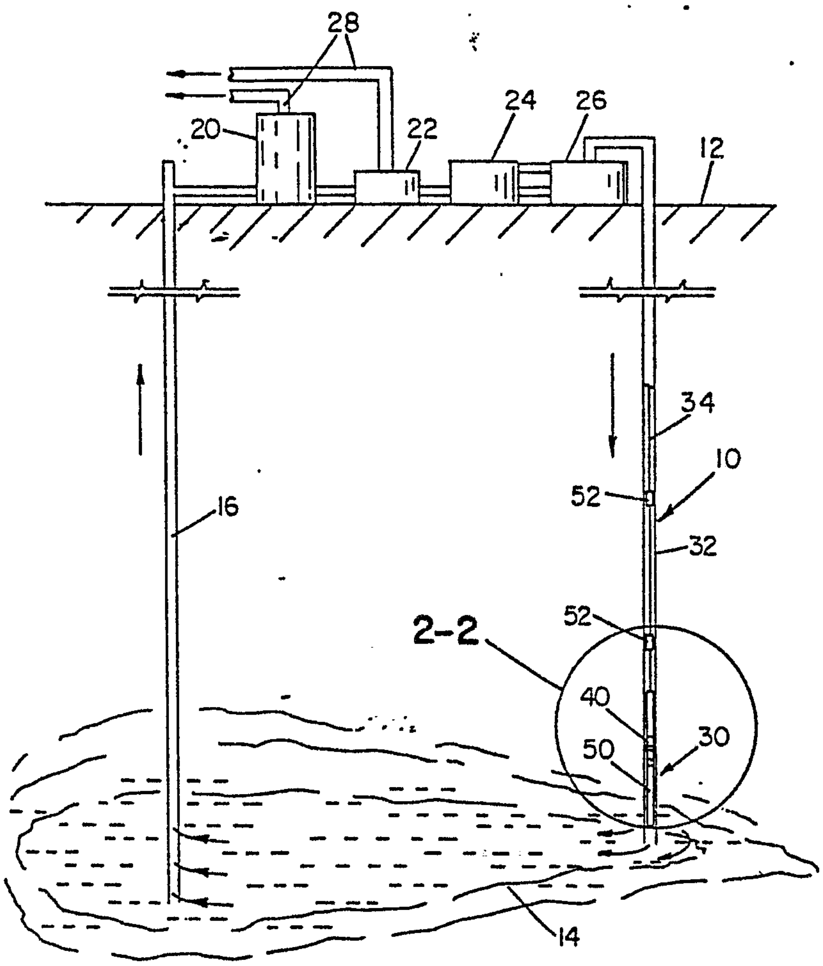
3. Burner of claim 1 or 2,
c h a r a c t e r i z e d in that
- said combustion chamber unit (224)
  - includes material (238)
    - bonding said sleeve (230) to said refractory tube (234)
      - that has a thermal gradient substantially greater than the thermal gradient of either said refractory material or said reinforcing sleeve
(Figs. 11 - 14).

4. Burner of any of claims 1 - 3,
c h a r a c t e r i z e d in that
- the material of said refractory tube (234)
  - is a silicon compound
(Figs. 11 - 14).

5. Burner of any of claims 1 - 4,
c h a r a c t e r i z e d in that
- said reinforcing sleeve (230) has
  - a thermally insulating coating (232) on its outer surface
(Figs. 11 - 14).

6. Burner of any of claims 1 - 5,
c h a r a c t e r i z e d in that
- said reinforcing sleeve (230)
  - is of high temperature metal alloy,
- said monolithic tube (234)
  - is of cast silicon carbide, and
- said bonding material (238)
  - includes aluminum oxide
(Figs. 11 - 14).

FIG 1



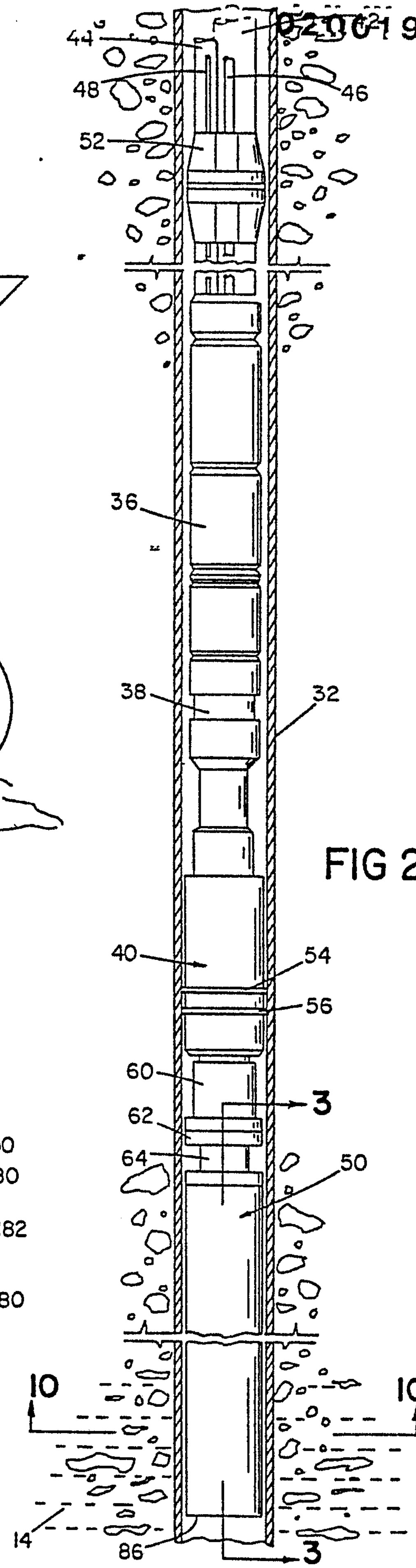


FIG 2

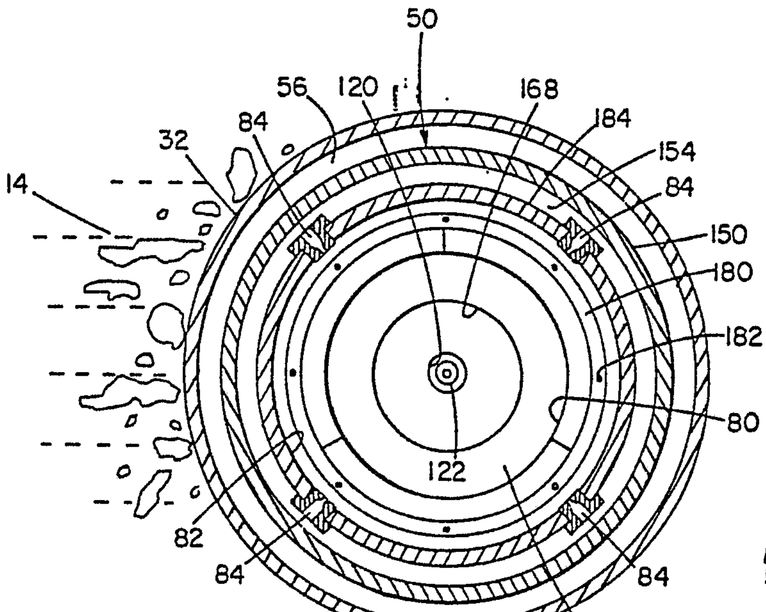
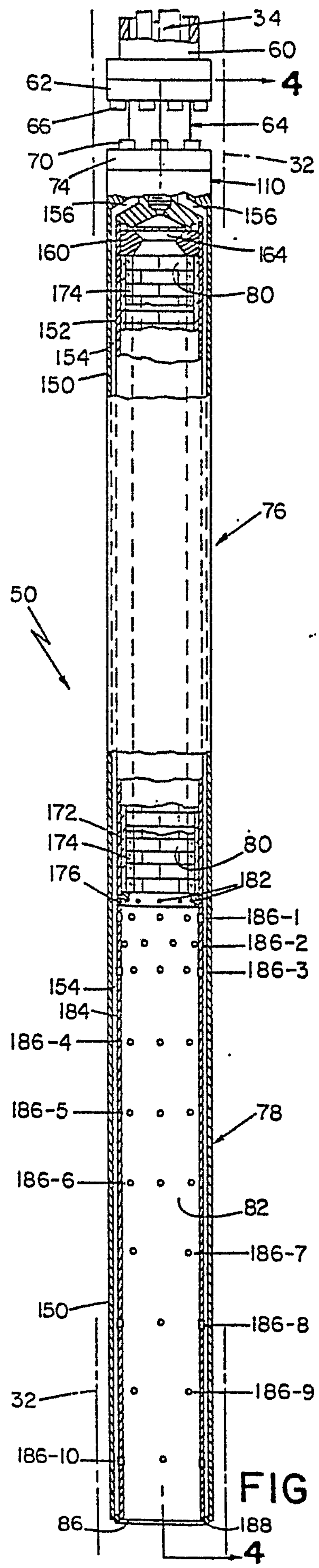


FIG 10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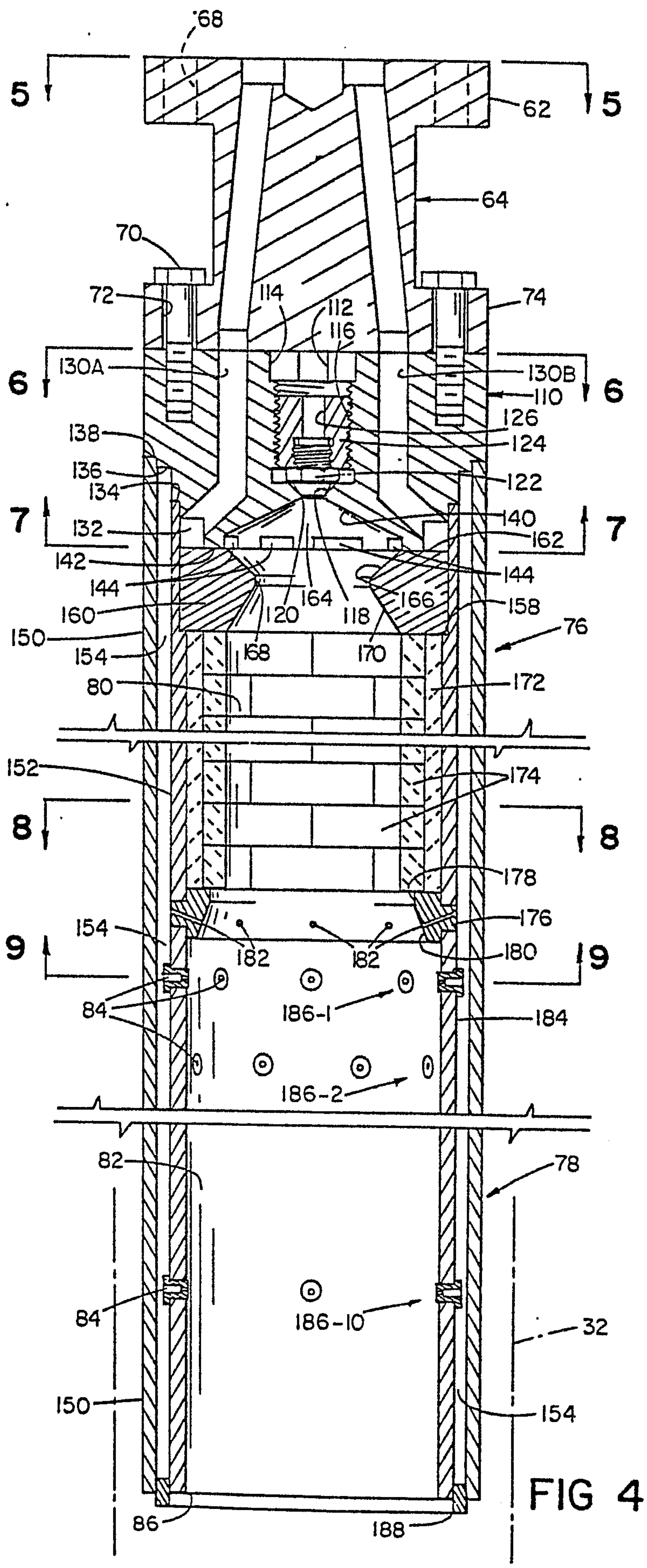
172
174
80
176
182
186-1
186-2
186-3
154
184
186-4
186-5
78
186-6
82
186-7
150
186-8
32
186-9
186-10
86
188
4

FIG 3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122
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76
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174
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8
178
154
176
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182
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150
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188

FIG 4

FIG 5

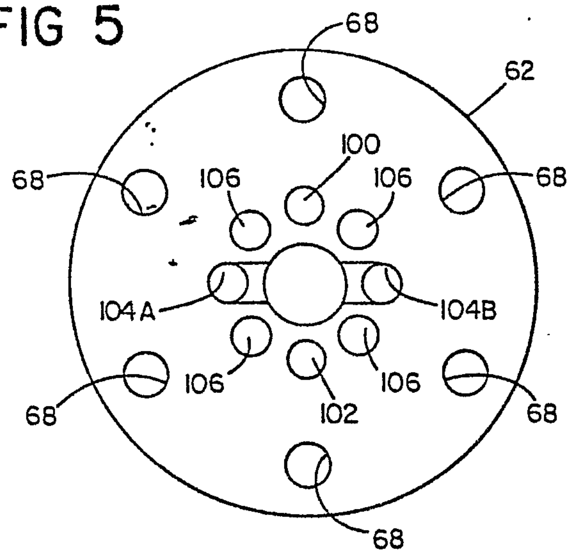


FIG 6

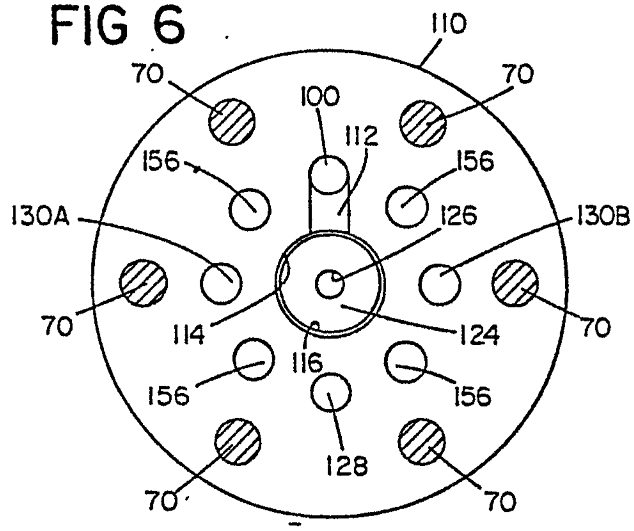


FIG 7

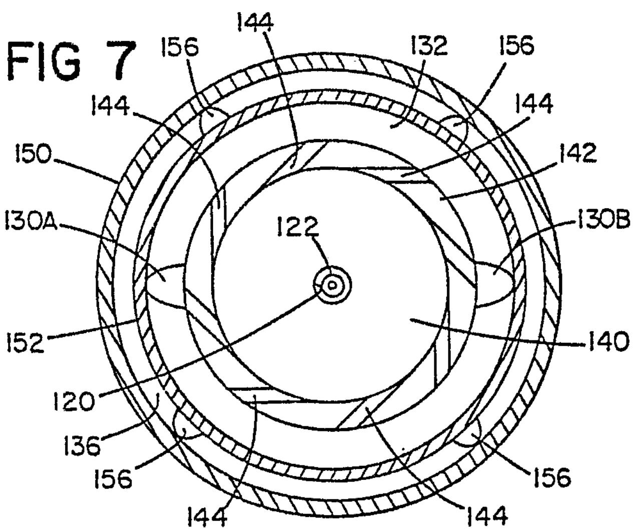


FIG 8

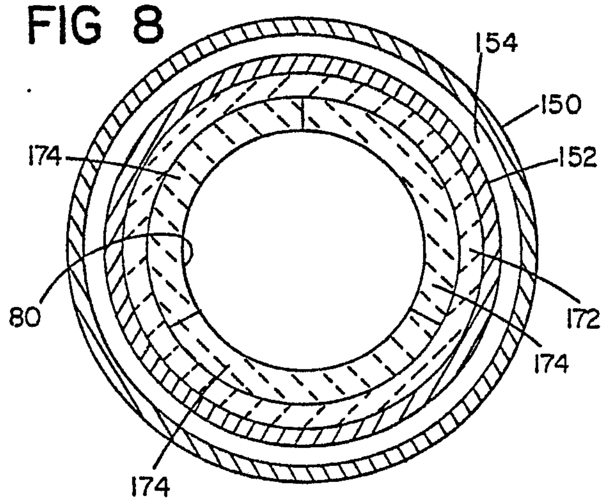


FIG 9

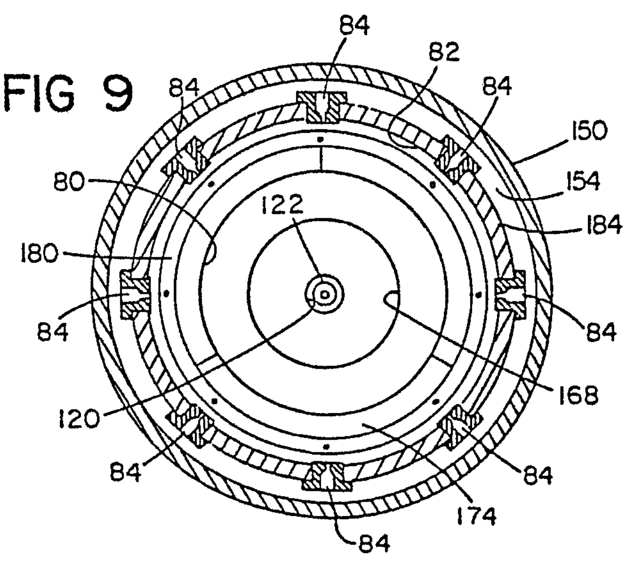
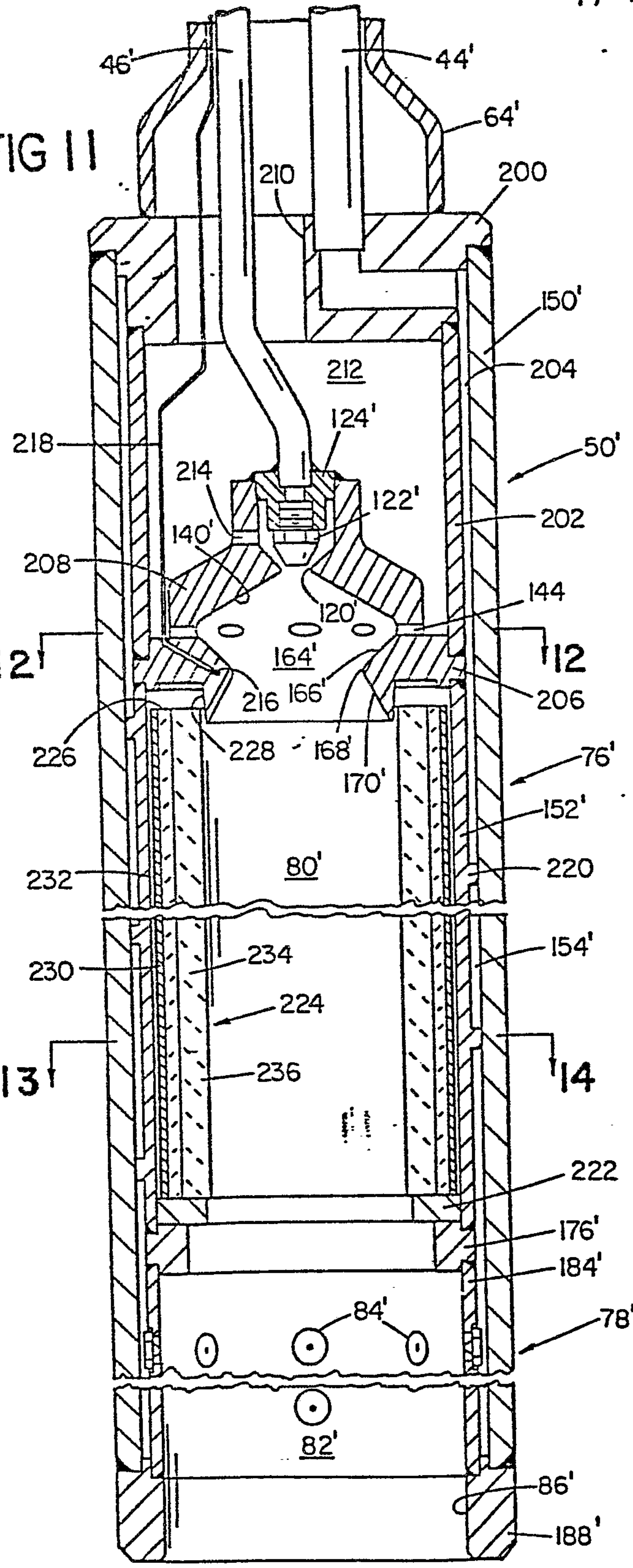


FIG 11



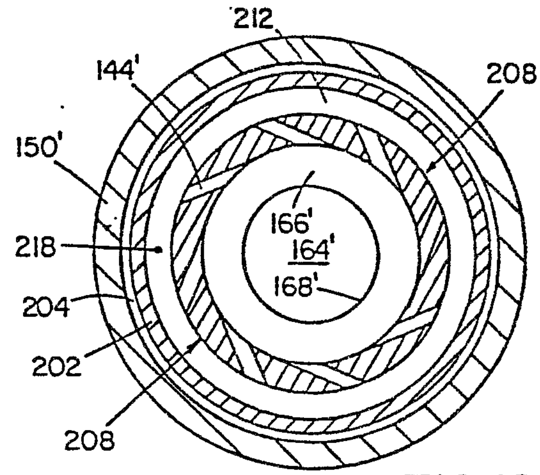


FIG 12

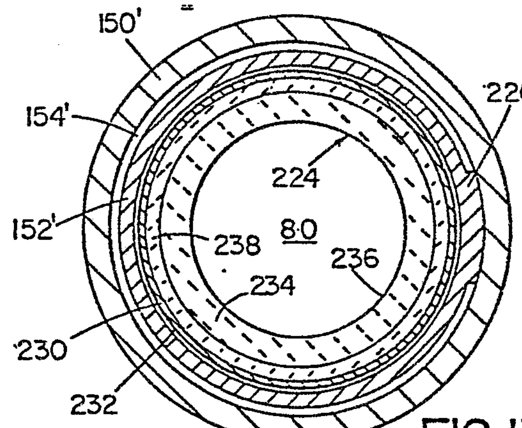
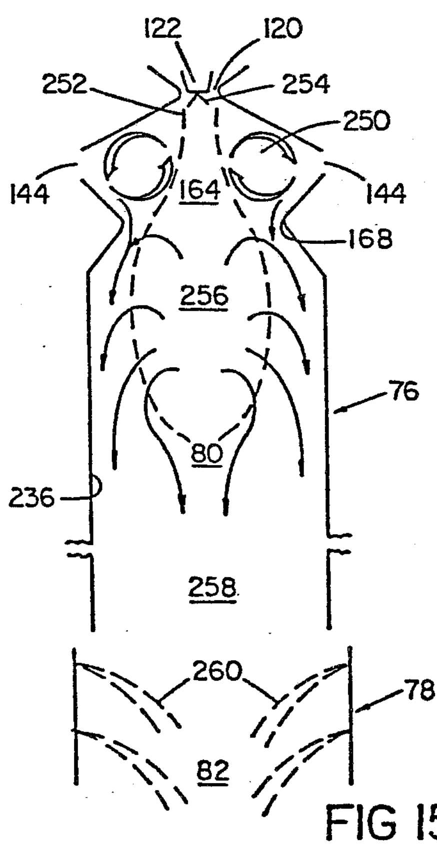


FIG 13



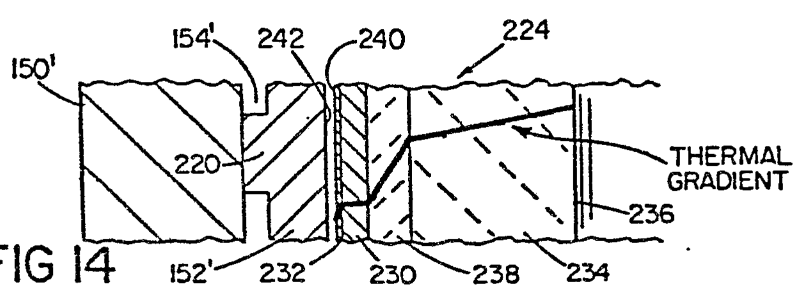


FIG 14

FIG 15