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(54) **METHOD OF OPERATING A MULTI-STAGE  
FLAMESHEET COMBUSTOR**

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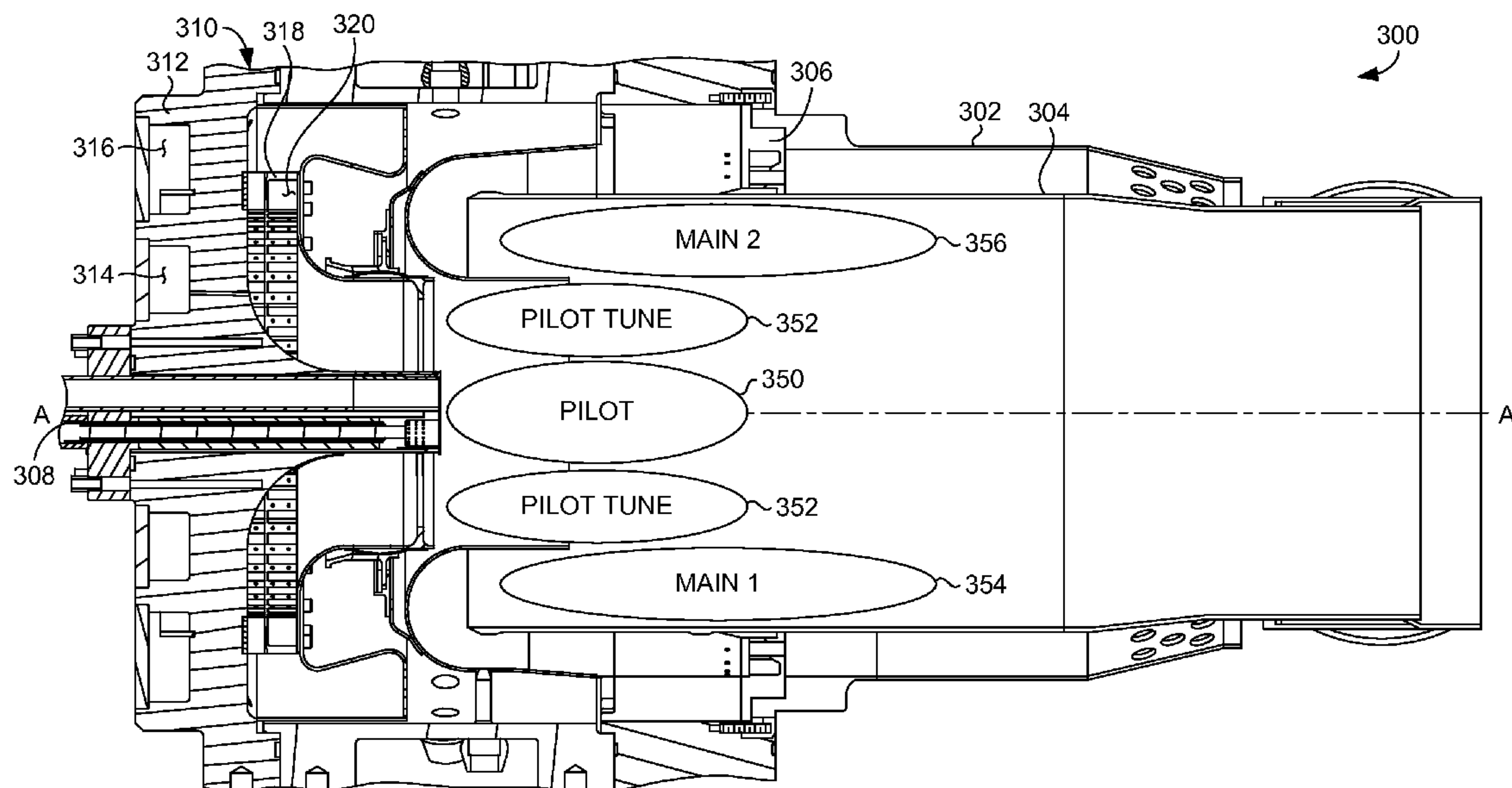
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(57) **ABSTRACT**

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The present invention discloses a novel way of controlling a gas turbine engine to reduce emissions levels when demand for power from the gas turbine engine is reduced. The operating system provides a series of operating modes for a gas turbine combustor through which fuel is staged to gradually increase engine power, yet harmful emissions, such as carbon monoxide are kept within acceptable levels.



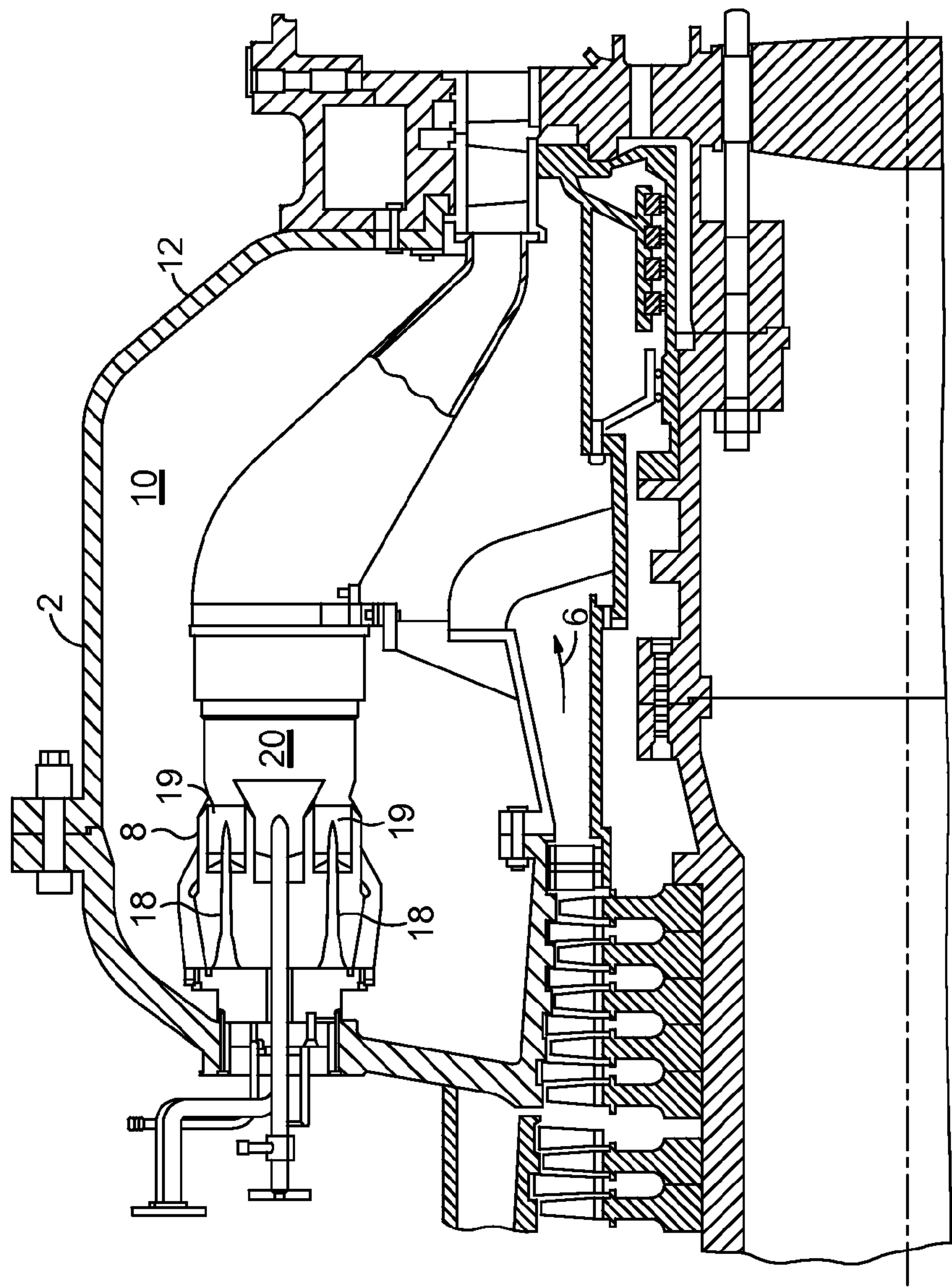
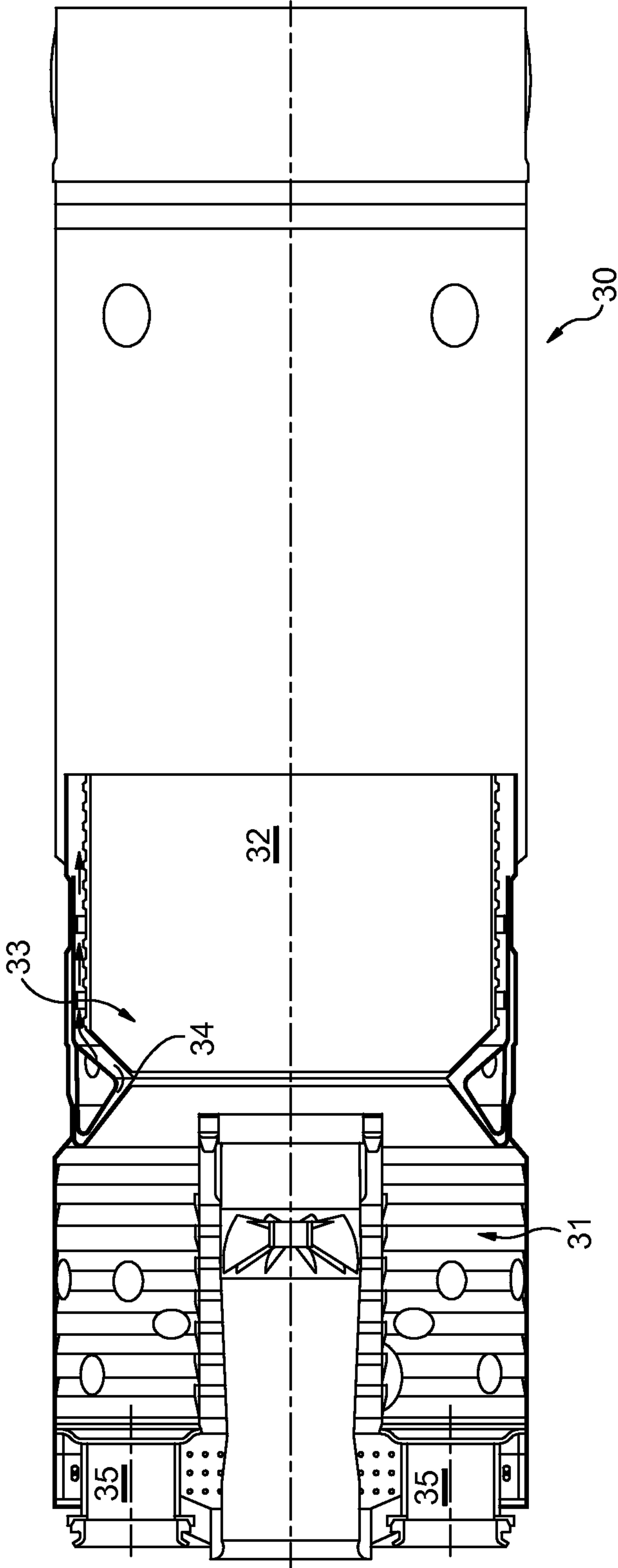


FIG. 1.  
PRIOR ART



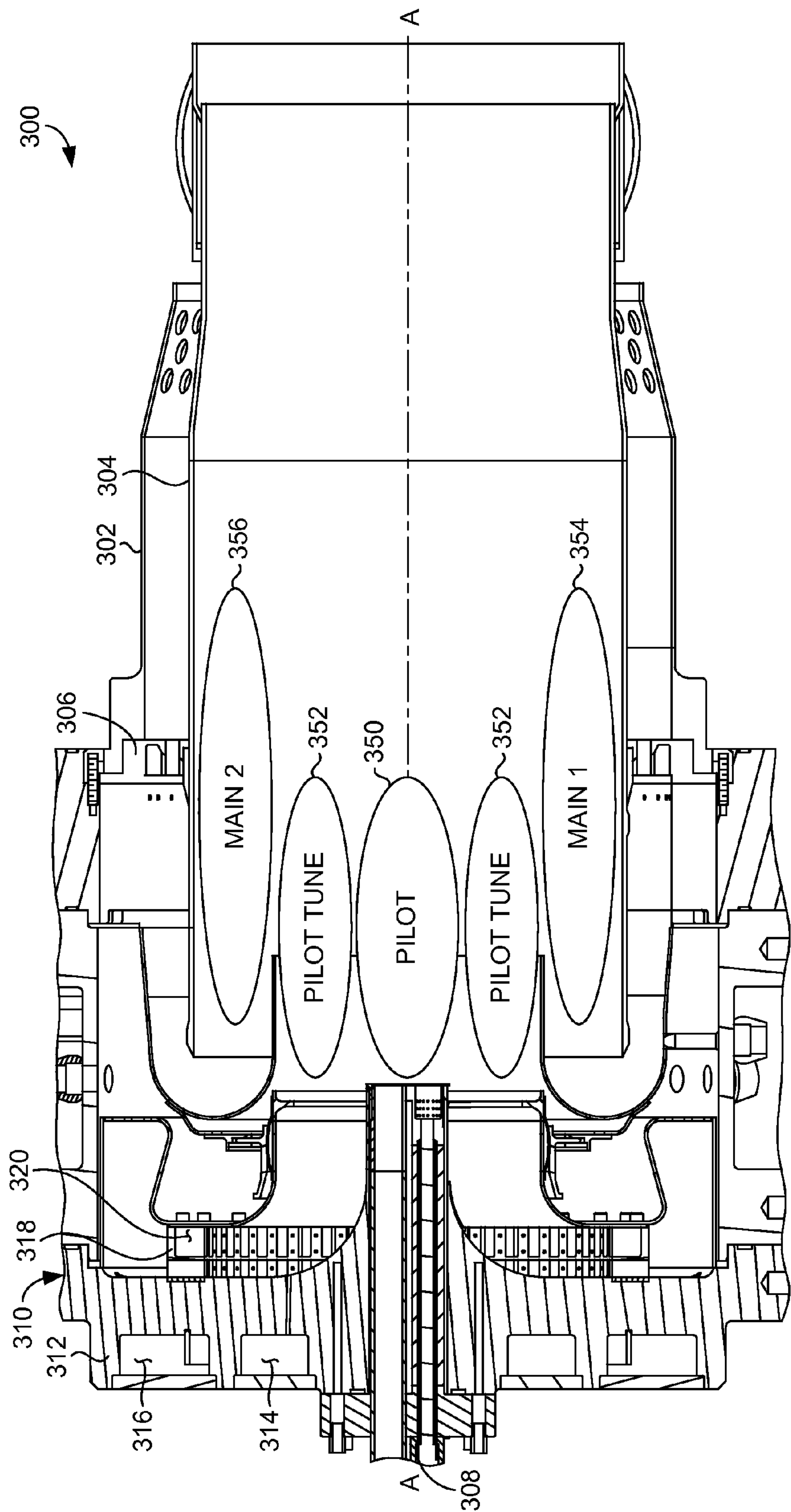


FIG. 3.

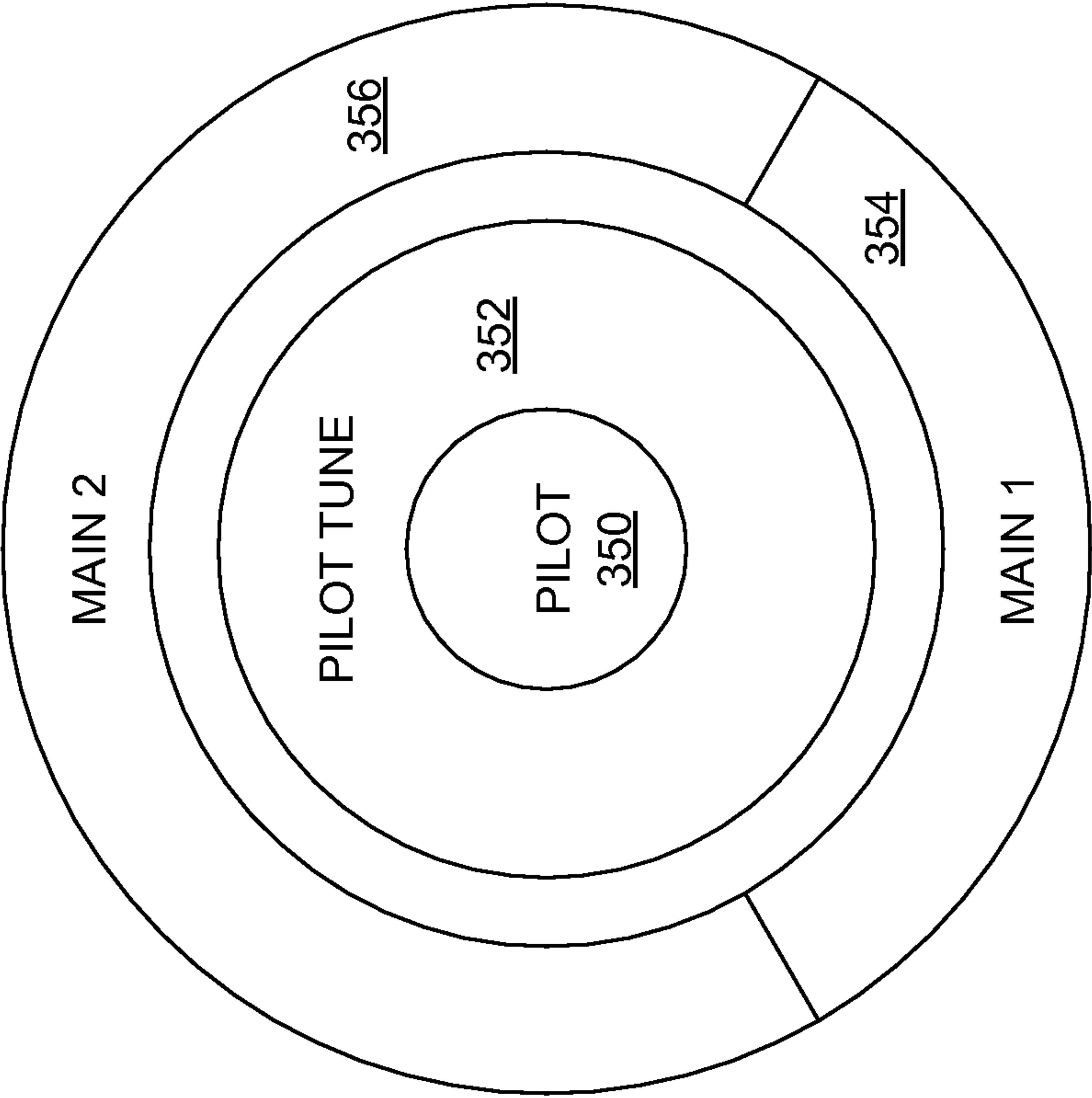
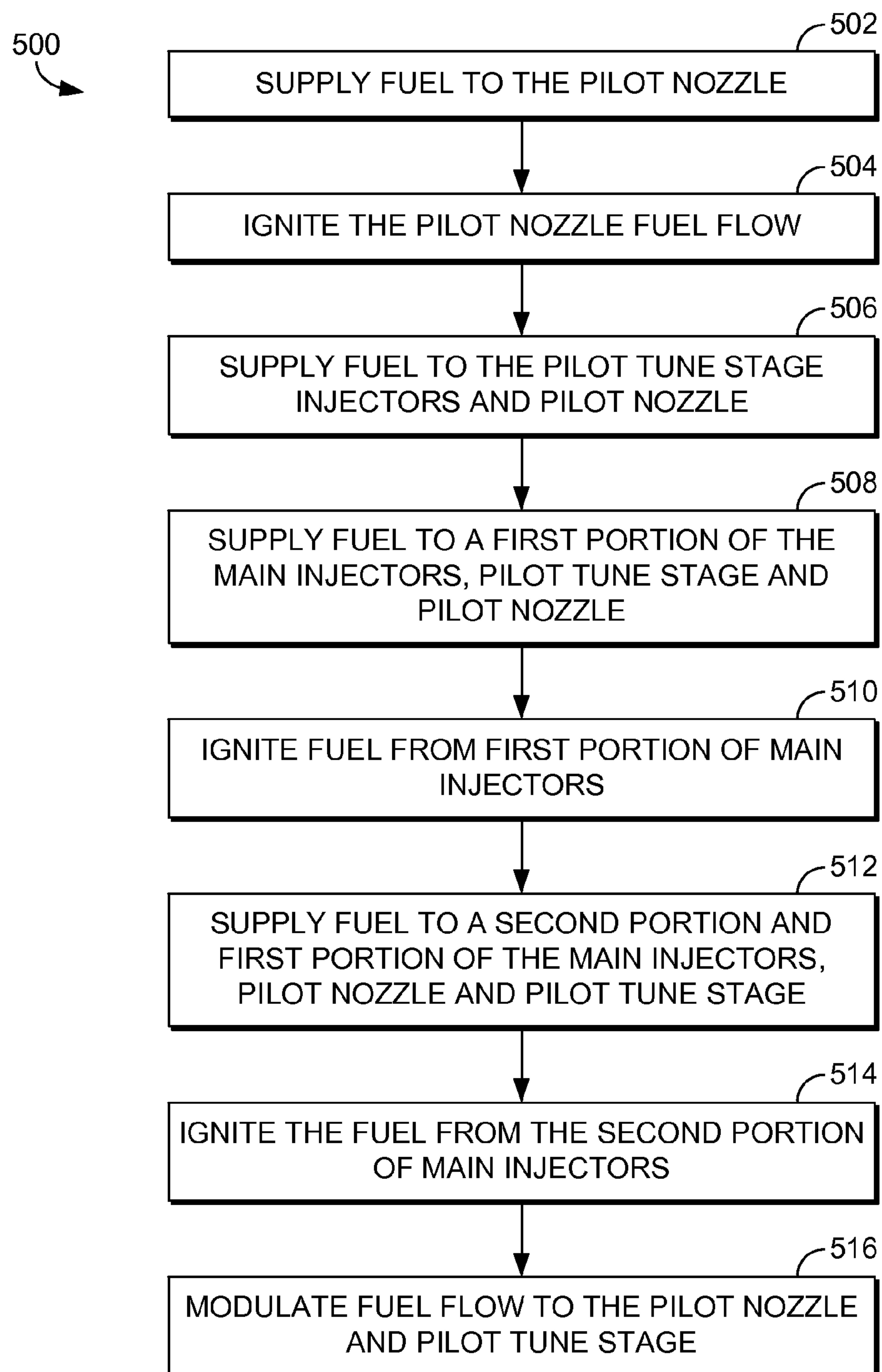


FIG. 4.

*FIG. 5.*



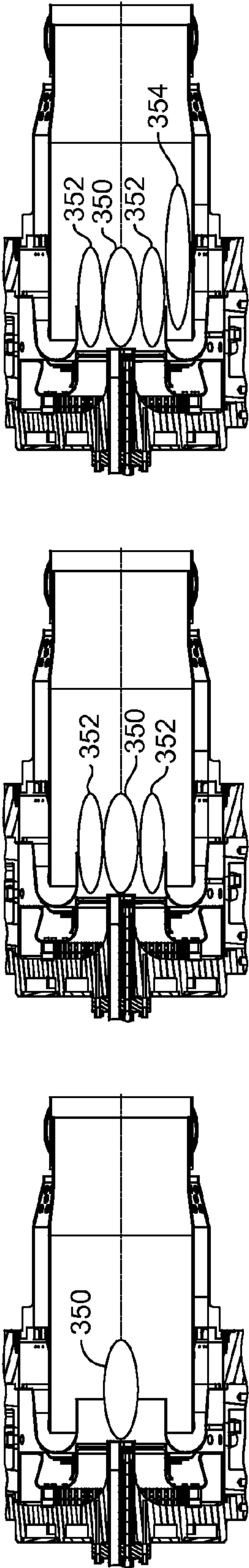


FIG. 6C.

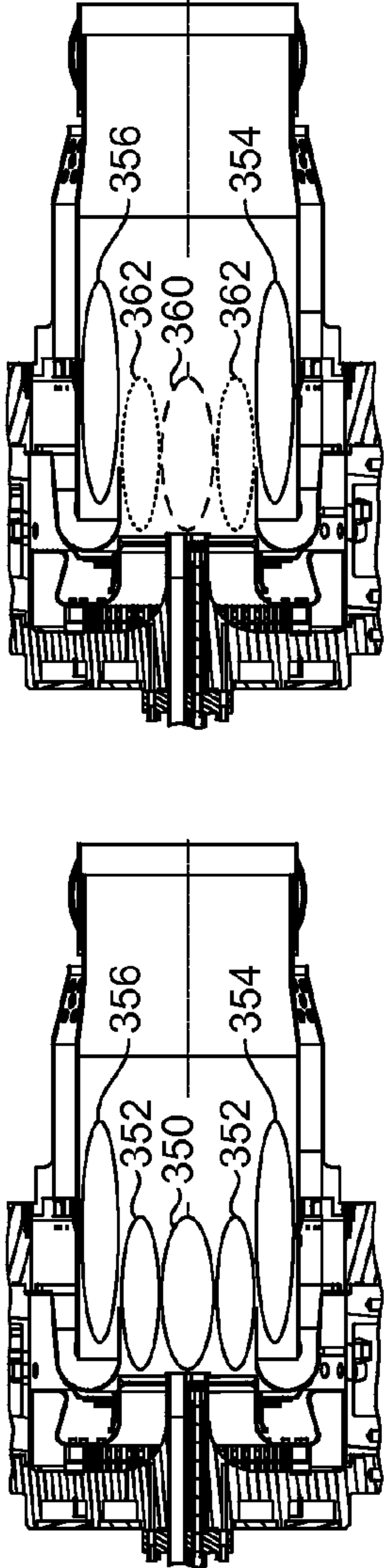


FIG. 6E.

FIG. 6D.

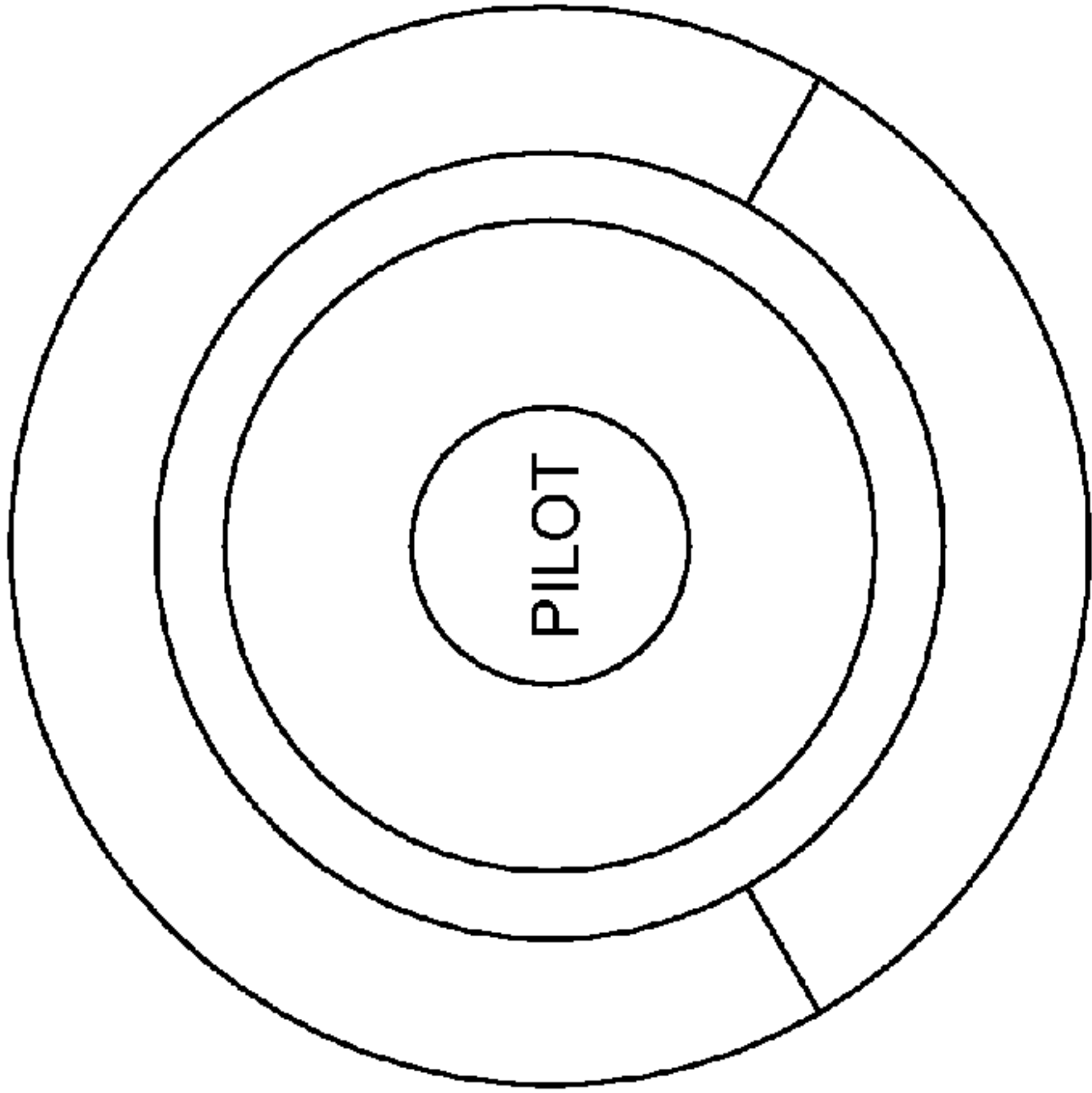


FIG. 7A.

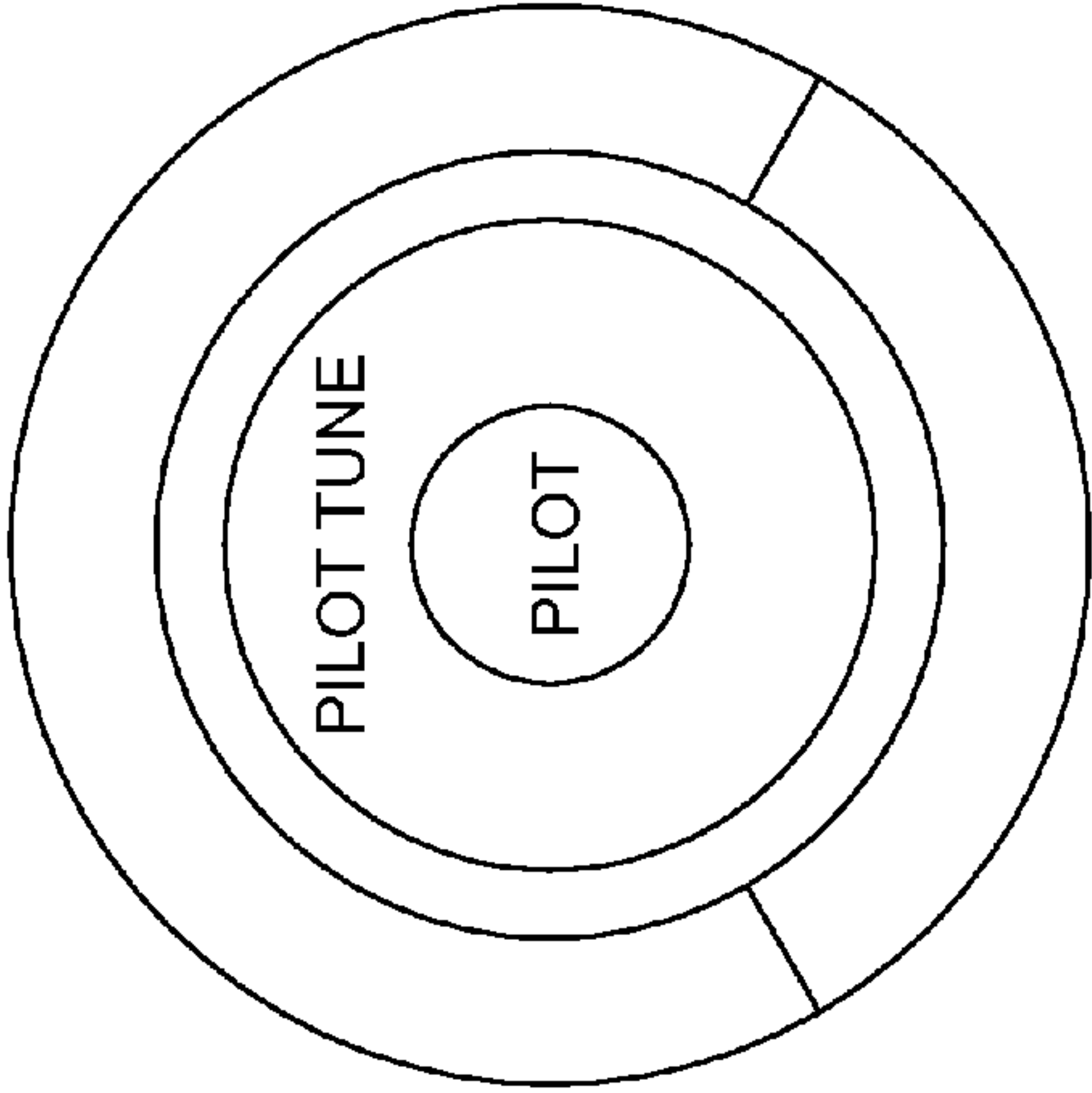


FIG. 7B.

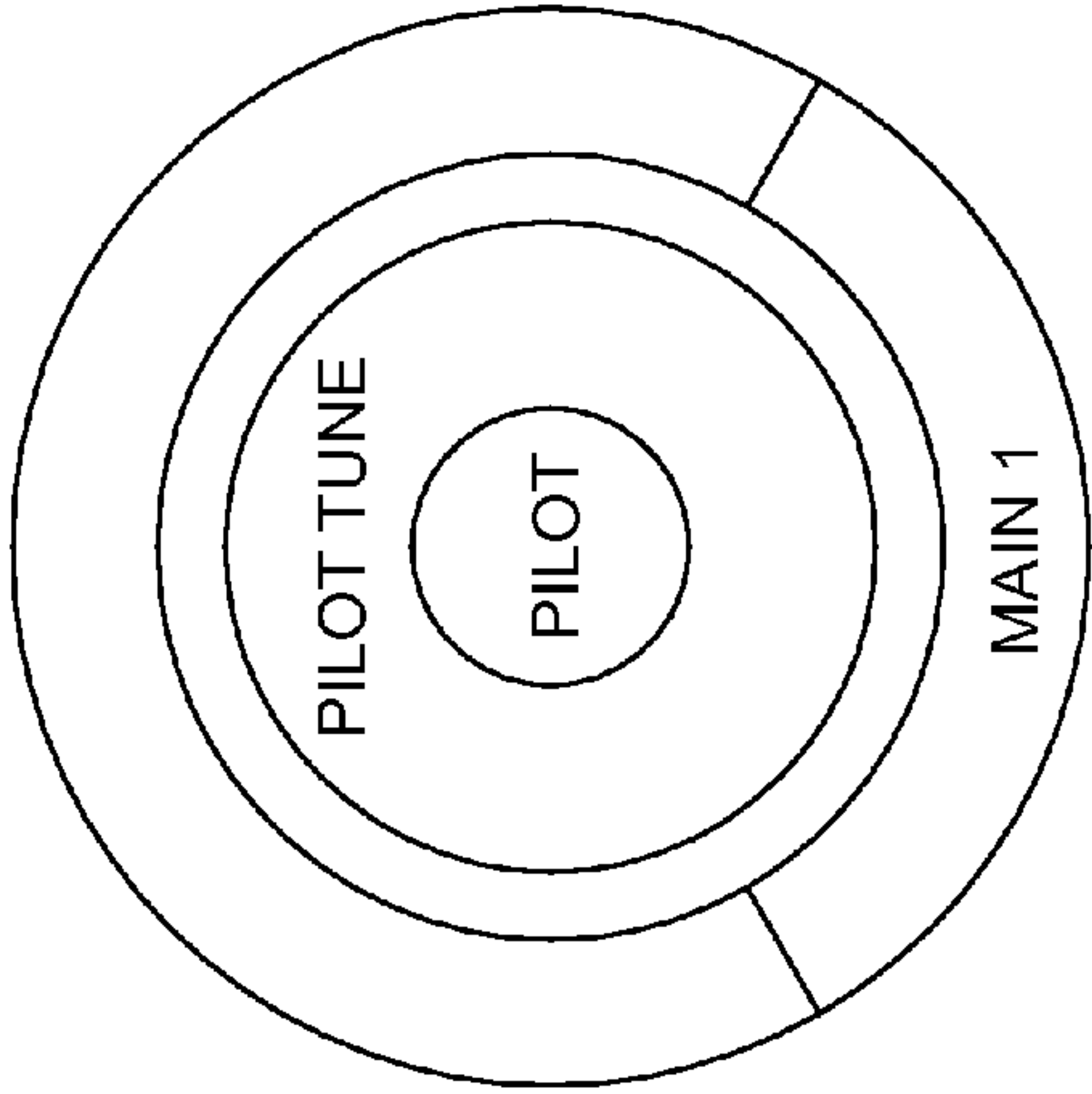


FIG. 7C.

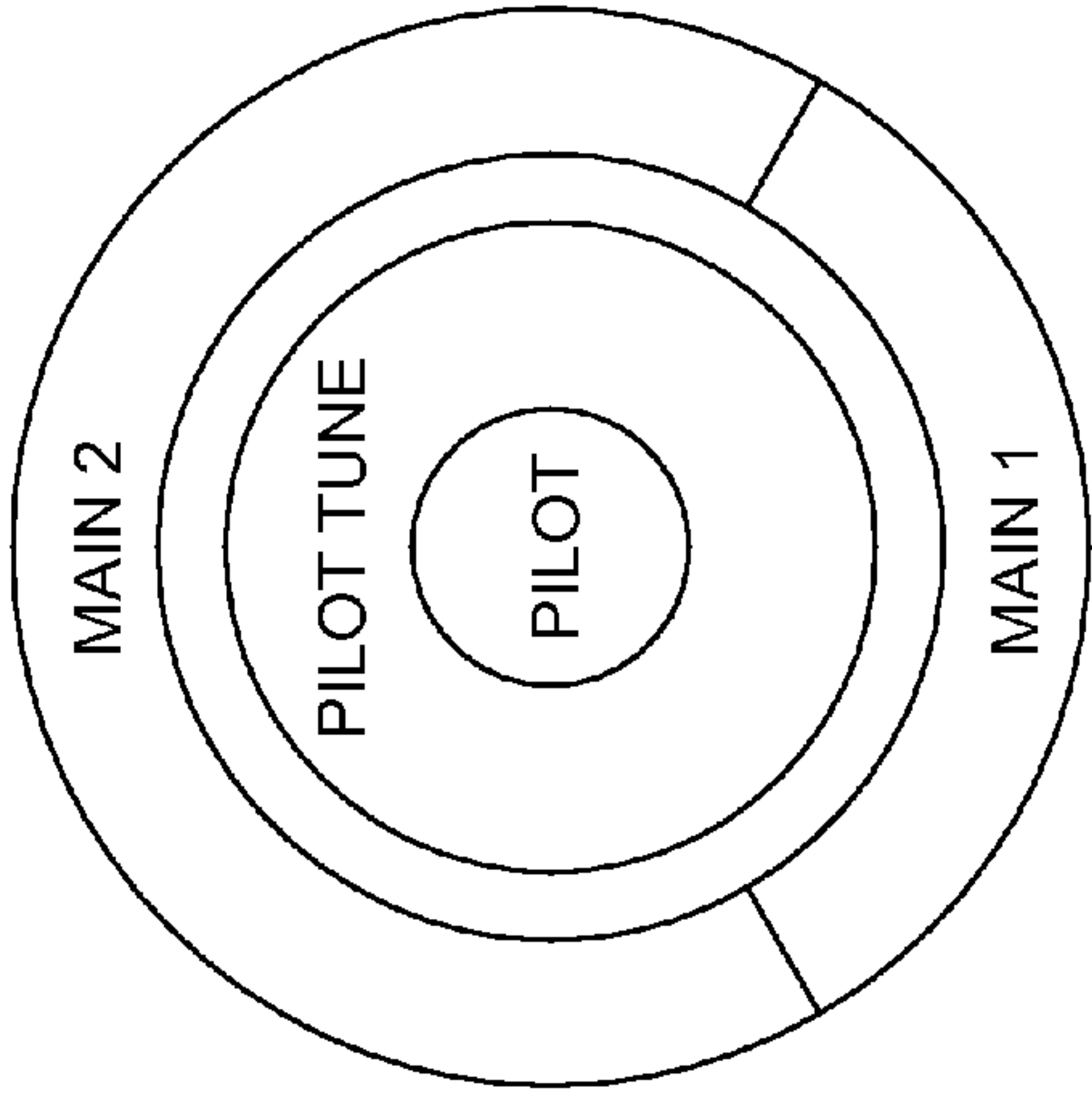
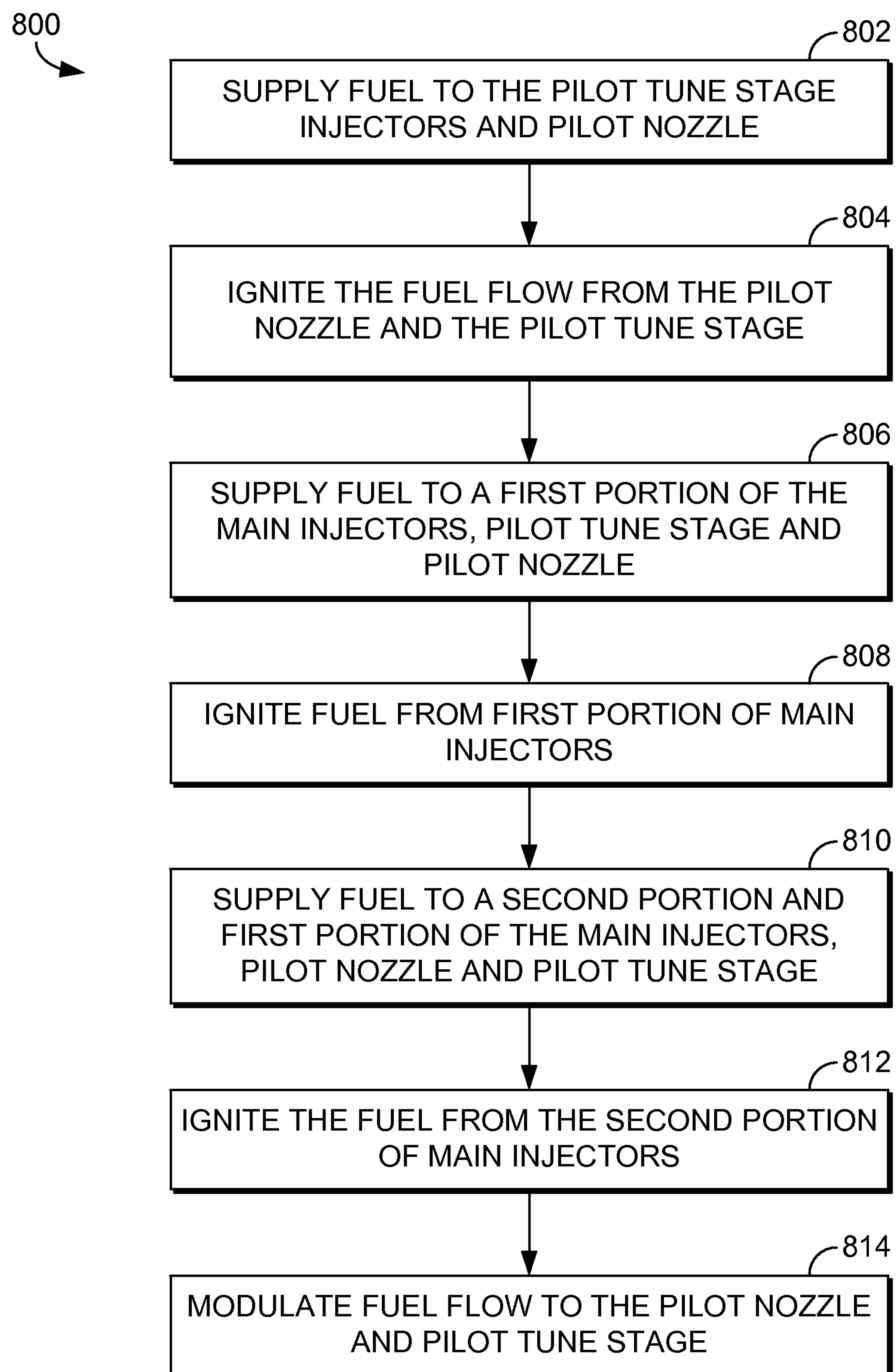
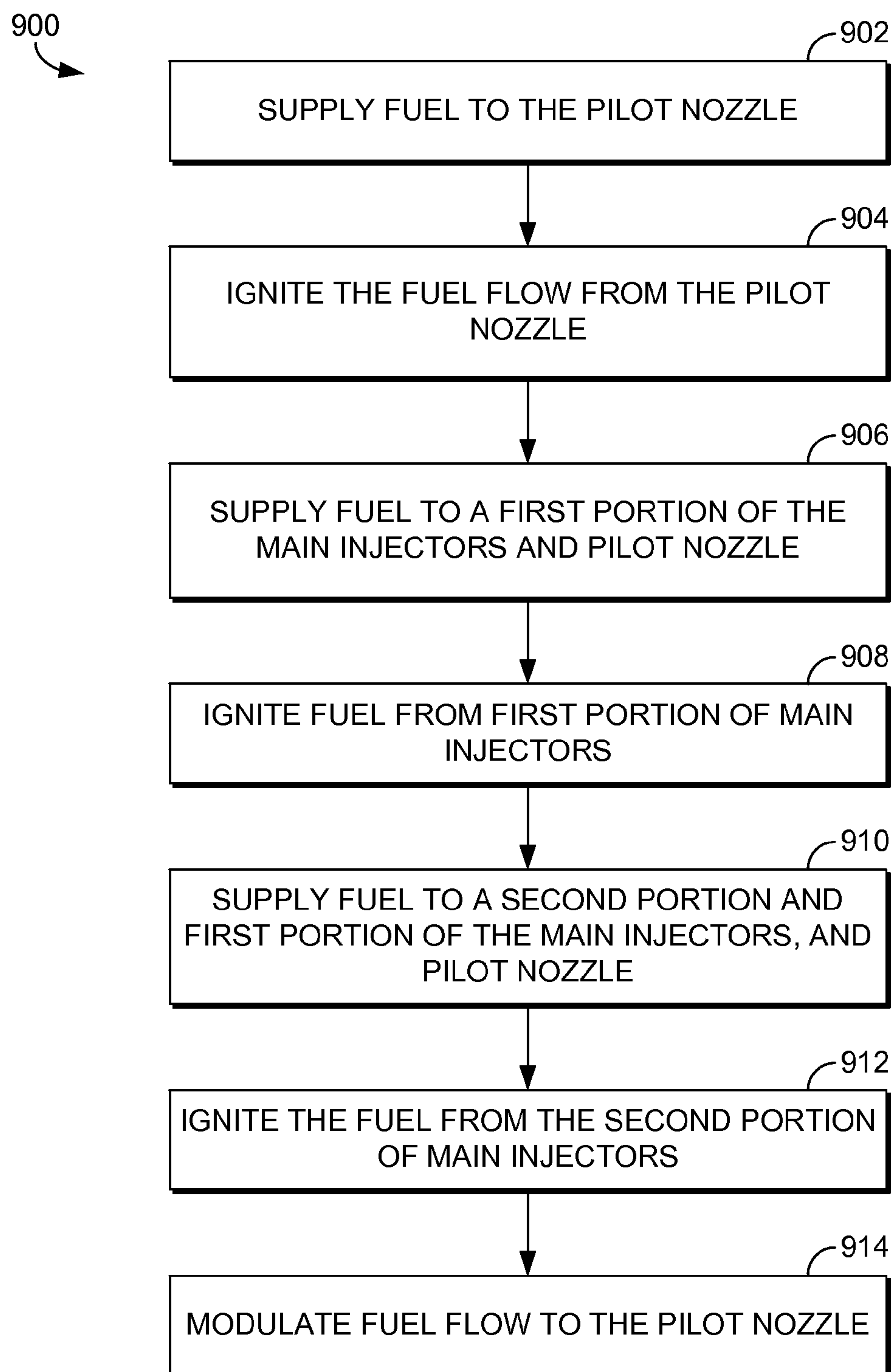


FIG. 7D.



*FIG. 8.*

*FIG. 9.*

## METHOD OF OPERATING A MULTI-STAGE FLAMESHEET COMBUSTOR

### CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of U.S. Provisional Patent Application Ser. No. 61/708,323 filed on Oct. 1, 2012.

### TECHNICAL FIELD

**[0002]** The present invention generally relates to a method for operating a combustion system in order to reduce emissions in a gas turbine combustor. More specifically, improvements in fuel staging for a combustor are provided.

### BACKGROUND OF THE INVENTION

**[0003]** In an effort to reduce the amount of pollution emissions from gas-powered turbines, governmental agencies have enacted numerous regulations requiring reductions in the amount of oxides of nitrogen (NOx) and carbon monoxide (CO). Lower combustion emissions can often be attributed to a more efficient combustion process, with specific regard to fuel injector location and mixing effectiveness.

**[0004]** Early combustion systems utilized diffusion type nozzles, where fuel is mixed with air external to the fuel nozzle by diffusion, proximate the flame zone. Diffusion type nozzles produce high emissions due to the fact that the fuel and air burn stoichiometrically at high temperature to maintain adequate combustor stability and low combustion dynamics.

**[0005]** An enhancement in combustion technology is the utilization of premixing, where the fuel and air mix prior to combustion to form a homogeneous mixture that burns at a lower temperature than a diffusion type flame and produces lower NOx emissions. Premixing can occur either internal to the fuel nozzle or external thereto, as long as it is upstream of the combustion zone. An example of a premixing combustor of the prior art is shown in FIG. 1. A combustor **8** has a plurality of fuel nozzles **18**, each injecting fuel into a premix cavity **19** where fuel mixes with compressed air **6** from plenum **10** before entering combustion chamber **20**. Premixing fuel and air together before combustion allows for the fuel and air to form a more homogeneous mixture, which will burn more completely, resulting in lower emissions. However, in this configuration the fuel is injected in relatively the same plane of the combustor, and prevents any possibility of improvement through altering the mixing length.

**[0006]** An alternate means of premixing and lower emissions can be achieved through multiple combustion stages, which allows for enhanced premixing as load increases. Referring now to FIG. 2, an example of a prior art multi-stage combustor is shown. A combustor **30** has a first combustion chamber **31** and a second combustion chamber **32** separated by a venturi **33**, which has a narrow throat region **34**. While combustion can occur in either first or second combustion chambers or both chambers, depending on load conditions, the lowest emissions levels occur when fuel, which is injected through nozzle regions **35**, is completely mixed with compressed air in first combustion chamber **31** prior to combusting in the second combustion chamber **32**. Therefore, this multi-stage combustor with a venturi is more effective at higher load conditions.

**[0007]** Gas turbine engines are required to operate at a variety of power settings. Where a gas turbine engine is coupled to drive a generator, required output of the engine is often measured according to the amount of load on the generator, or power that must be produced by the generator. A full load condition is the point where maximum output is drawn from the generator and therefore requires a maximum power from the engine to drive the generator. This is the most common operating point for land-based gas turbines used for generating electricity. However, often times electricity demands do not require the full capacity of the generator, and the operator desires for the engine to operate at a lower load setting, such that only the load demanded is being produced, thereby saving fuel and lowering operating costs. Combustion systems of the prior art have been known to become unstable at lower load settings, especially below 50% load, while also producing unacceptable levels of NOx and CO emissions. This is primarily due to the fact that most combustion systems are staged for most efficient operation at high load settings. The combination of potentially unstable combustion and higher emissions often times prevents engine operators from running engines at lower load settings, forcing the engines to either run at higher settings, thereby burning additional fuel, or shutting down, and thereby losing valuable revenue that could be generated from the part-load demand.

**[0008]** A problem with shutting down the engine is the additional cycles incurred by the engine hardware. A cycle is commonly defined as the engine passing through the normal operating envelope. That is, by shutting down an engine, the engine hardware accumulates additional cycles. Engine manufacturers typically rate hardware life in terms of operating hours or equivalent operating cycles. Therefore, incurring additional cycles can reduce hardware life and require premature repair or replacement at the engine operator's expense. What is needed is a system that can provide flame stability and low emissions benefits at a part load condition, as well as at a full load condition, such that an engine can be efficiently operated at lower load conditions, thereby eliminating the wasted fuel when high load operation is not demanded or incurring the additional cycles on the engine hardware when shutting down.

### SUMMARY

**[0009]** The present invention discloses a method of operating a gas turbine engine, and more specifically, operating the gas turbine combustor in a way to improve the turndown efficiency of the engine. In an embodiment of the present invention, a method of operating the combustor comprises supplying fuel to a pilot nozzle, igniting the fuel from the pilot nozzle, and supplying additional fuel to a stage of pilot tune injectors. The method also discloses supplying fuel to a first portion of the combustor main fuel injectors, ignition of this fuel to establish a main combustion flame, supplying fuel to a second portion of the combustor main fuel injectors and ignition of this fuel to support the main combustion flame.

**[0010]** In an alternate embodiment of the present invention, a computerized method for staging fuel in a gas turbine combustor is provided. The method provides a way of operating a combustor having a pilot nozzle, a set of pilot tune injectors, and a main set of fuel injectors through four different modes of operation. Each sequential mode of operation adds additional fuel flow to the combustor.

**[0011]** In yet another embodiment of the present invention, a method of improving the turndown capability of a gas



turbine combustor while controlling carbon monoxide production is disclosed. The method modulates fuel flow to a first portion and a second portion of an annular array of fuel injectors and modulates the fuel flow to one or more injectors in a core section of the gas turbine combustor, where the core section comprises a pilot nozzle and a set of injectors for tuning the pilot nozzle. Modulation of these fuel circuits permits an overall reduction in fuel flow to support turndown capability while maintaining operation within acceptable emissions limits.

**[0012]** In a further embodiment of the present invention, a method of operating the combustor comprises supplying fuel to both a pilot fuel nozzle and a stage of pilot tune injectors. The fuel injected through these circuits is ignited and then additional fuel is added via a first portion of the main fuel injectors, which is ignited to generate a main combustion flame. Then, fuel is supplied to a second portion of the main fuel injectors, and this additional fuel is then ignited in order to further support the main combustion flame.

**[0013]** In an additional embodiment of the present invention, a method of operating the combustor comprises supplying fuel to a pilot nozzle and igniting this fuel to form a pilot flame. Additional fuel is added to the combustor by supplying fuel to a first portion of the main fuel injectors. The fuel added via the first portion of main injectors is ignited to form a main combustion flame. Then, fuel is supplied to a second portion of the main fuel injectors and ignited in order to further support the main combustion flame.

**[0014]** Additional advantages and features of the present invention will be set forth in part in a description which follows, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned from practice of the invention. The instant invention will now be described with particular reference to the accompanying drawings.

#### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

**[0015]** The present invention is described in detail below with reference to the attached drawing figures, wherein:

**[0016]** FIG. 1 is a cross section of a gas turbine combustor of the prior art.

**[0017]** FIG. 2 is a cross section of an alternate combustor of the prior art.

**[0018]** FIG. 3 is a cross section of a gas turbine combustor in accordance with an embodiment of the present invention.

**[0019]** FIG. 4 is an end view of the gas turbine combustor of FIG. 1 in accordance with an embodiment of the present invention.

**[0020]** FIG. 5 is a flow diagram depicting a process of controlling a gas turbine combustor in accordance with an embodiment of the present invention.

**[0021]** FIG. 6A is a cross section view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a first mode.

**[0022]** FIG. 6B is a cross section view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a second mode.

**[0023]** FIG. 6C is a cross section view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a third mode.

**[0024]** FIG. 6D is a cross section view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a fourth mode.

**[0025]** FIG. 6E is a cross section view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a modulated version of the fourth mode of FIG. 6D.

**[0026]** FIG. 7A is an end view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a first mode.

**[0027]** FIG. 7B is an end view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a second mode.

**[0028]** FIG. 7C is an end view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a third mode.

**[0029]** FIG. 7D is an end view of a gas turbine combustor in accordance with an embodiment of the present invention operating in a fourth mode.

**[0030]** FIG. 8 is a flow diagram depicting a process of controlling a gas turbine combustor in accordance with an alternate embodiment of the present invention.

**[0031]** FIG. 9 is a flow diagram depicting a process of controlling a gas turbine combustor in accordance with yet another embodiment of the present invention.

#### DETAILED DESCRIPTION

**[0032]** By way of reference, this application incorporates the subject matter of U.S. Pat. Nos. 6,935,116, 6,986,254, 7,137,256, 7,237,384, 7,308,793, 7,513,115, and 7,677,025.

**[0033]** The present invention discloses a way of operating a combustion system in order to improve the turndown capability of the gas turbine engine. That is, embodiments of the invention disclosed provide means for improved combustion stability within the gas turbine combustor when the demand for power from a generator is lower and thus less output from the engine is required.

**[0034]** The present invention will now be discussed with respect to FIGS. 3-9. An embodiment of a gas turbine combustor on which the improved operating methodology of the present invention can be applied is depicted in FIG. 3. The combustion system 300 extends about a longitudinal axis A-A and includes a flow sleeve 302 for directing a predetermined amount of compressor air along an outer surface of a combustion liner 304. Main fuel injectors 306 are positioned radially outward of the combustion liner 304 and are designed to provide a fuel supply to mix with compressed air along a portion of the outer surface of the combustion liner 304, prior to entering the combustion liner 304. The fuel injected by the main fuel injectors 306 mixes with compressed air and travels in a forward direction towards the inlet region of the combustion liner 304, where the fuel/air mixture then reverses direction and enters the combustion liner 304. Extending generally along the longitudinal axis A-A is a pilot fuel nozzle 308 for providing and maintaining a pilot flame for the combustion system. The pilot flame is used to ignite, support and maintain multiple stages of fuel injectors of combustion system 300.

**[0035]** The combustion system 300 also includes a radially staged premixer 310. The premixer 310 comprises an end cover 312 having a first fuel plenum 314 extending about the longitudinal axis A-A of the combustion system 300 and a second fuel plenum 316 positioned radially outward of the first fuel plenum 314 and concentric with the first fuel plenum 314. The radially staged premixer 310 also comprises a radial inflow swirler 318 having a plurality of vanes 320 oriented in a direction that is at least partially perpendicular to the longitudinal axis A-A of the combustion system 300.



[0036] The pilot fuel nozzle **308** is connected to a fuel supply (not shown) and provides fuel to the combustion system **300** for supplying a pilot flame **350** where the pilot flame **350** is positioned generally along the longitudinal axis A-A. The radially staged premixer **310** including the fuel plenums **314** and **316**, radial inflow swirler **318** and its plurality of vanes **320** provide a fuel-air mixture through the vanes **320** for supplying additional fuel to the pilot flame **350** by way of a pilot tune stage, or P-tune, **352**.

[0037] As discussed above, combustion system **300** also includes main fuel injectors **306**. For the embodiment of the present invention shown in FIG. 3, the main fuel injectors **306** are located radially outward of the combustion liner **304** and spread in an annular array about the combustion liner **304**. The main fuel injectors **306** may comprise one or more portions and stages extending equally or unequally about a circumference of the main fuel stage. As an example of an application for the described invention, the main fuel injectors are divided into two stages, a first portion and a second portion. The first portion extends approximately 120 degrees, while the second portion extends approximately the remaining 240 degree span. The first portion of the main fuel injectors **306** generate a Main 1 flame **354** while the second portion of the main fuel injectors **306** generate a Main 2 flame **356**, as shown in FIG. 4.

[0038] Referring to FIG. 4, an aft view, looking forward into the gas turbine combustor of FIG. 3 is depicted. FIG. 4 clearly displays the radial and circumferential location of each of the flame locations within combustion system **300**, with pilot flame **350** at the center, pilot tune stage **352** located radially outward of the pilot flame **350** and Main 1 flame **354** and Main 2 flame **356** located radially outward of the pilot tune stage **352**.

[0039] As described above, a gas turbine engine incorporates a plurality of combustors. Generally, for the purpose of discussion, the gas turbine engine may include low emission combustors such as those disclosed herein and may be arranged in a can-annular configuration about the gas turbine engine. One type of gas turbine engine (e.g., heavy duty gas turbine engines) may be typically provided with, but not limited to, 6 to 18 individual combustors, each of the combustors fitted with the components outlined above. Accordingly, based on the type of gas turbine engine, there may be several different fuel circuits utilized for operating the gas turbine engine. For an embodiment of the present invention, there are four fuel circuits employed. However, it is envisioned that the specific fuel circuitry and associated control mechanisms could be modified to include fewer or additional fuel circuits.

[0040] Having discussed the physical arrangement of the combustion system **300** in which the present invention operates, reference will now be made to FIGS. 5-9 for a detailed description of the methods of operation for this combustion system. The present invention utilizes four fuel stages for tuning and operational flexibility. More specifically, with respect to FIG. 5, a method **500** of operating the combustion system **300** of FIG. 3 is outlined, in which four different fuel stages are utilized to enhance combustion stability so as to allow for operation at lower load settings. Initially in a step **502**, fuel is supplied to a pilot fuel nozzle of the gas turbine combustor. Then, in a step **504**, the fuel from the pilot fuel nozzle is ignited to form a pilot flame. This ignition can occur through a variety of ignition sources such as a spark igniter or a torch igniter. As the pilot fuel nozzle is generally located

along the longitudinal axis of the combustor, the resulting pilot flame is also located generally along the longitudinal axis. These steps of supplying fuel to the pilot fuel nozzle and igniting the fuel to form the pilot flame is considered Mode 1 of operation of the combustion system and operates within an operational range starting with the ignition or "light-off" of the pilot fuel nozzle and continues through a "full speed no load" or "FSNL" condition. FSNL, as discussed above, is the engine operating condition where the turbine and compressor are operating at the maximum designed rotational speed, which for a 60 Hz engine, is approximately 3600 revolutions per minute, but no load is being applied by the generator. A depiction of Mode 1 operation of the combustion system is shown in both FIGS. 6A and 7A.

[0041] As one skilled in the art understands, a flame inherently contains a shear layer. Generally speaking, a shear layer, or boundary layer is a region of flow in which there can be significant velocity gradient. The shear layer of a flame is the shared region between the outermost edge of the flame and the non-flammable surroundings or an adjacent flame.

[0042] Ignition of fuel from a main set of fuel injectors can occur more easily and reliably due to the ability to control the fuel/air ratio of the shear layer of the pilot flame. More specifically, by locally increasing the supply of fuel at an outermost radial location in the premix passage, the concentration of fuel in the shear layer of the resulting pilot flame is increased. As a result, the richened shear layer allows the main injectors to more easily and reliably ignite without the need for a lot of energy, which then results in lower pulsation levels during ignition of the main fuel injectors.

[0043] An additional benefit of being able to locally richen the fuel flow to the shear layer is the ability to maintain a stable process of igniting the fuel being injected by the main injectors. That is, in a premixed combustion system, fuel flow levels are traditionally kept as lean as possible in order to reduce emissions. By locally adding fuel to the shear layer during a selective time period, a more fuel-rich mixture is established, thereby increasing the fuel/air ratio in the shear layer region. A more fuel-rich mixture provides more favorable conditions for ignition to occur and increases the stability of the flame. Once the flame is ignited, then the level of fuel richness can be reduced to a leaner mixture without jeopardizing the stability of the flame.

[0044] In a step **506**, fuel continues to be supplied to the pilot fuel nozzle, as in the step **502** while also being supplied to a set of pilot tune stage injectors. The pilot tune stage injectors are located in the plurality of vanes **320** of radial inflow swirler **318**, which are located radially outward of the pilot fuel nozzle **308**, and inject fuel from the fuel plenums of the end cover to mix with a surrounding airflow. This fuel-air mixture then passes along the pilot flame and is used to enhance and support the pilot flame as well as to richen the shear layer of the pilot flame. The operation of the pilot fuel nozzle and set of pilot tune stage injectors together is considered Mode 2 of operation for the combustion system. Mode 2 can operate from light-off up until approximately 10% load. A depiction of the Mode 2 operation of the combustion system is shown in both FIGS. 6B and 7B where fuel/air mixture from the pilot tune stage is shown radially outward of and encompassing the pilot flame.

[0045] Next, in a step **508**, the combustion system enters a Mode 3 of operation where fuel is supplied to a first portion of the main fuel injectors, while also still being supplied to the pilot fuel nozzle and the set of pilot tune stage injectors. As



discussed above, the main fuel injectors **306** of the combustion system are arranged in an annular array about the combustion liner and are divided into two portions—a first portion extending approximately 120 degrees around the combustion liner **304** and a second portion extending approximately 240 degrees about the combustion liner **304**. In a step **510**, the fuel injected in the step **508** by the first portion of the main fuel injectors is ignited to form a main combustion flame. Ignition of the main combustion flame occurs as a result of the established pilot flame through Modes 1 and 2. However, to ignite this main combustion flame, the combustion system typically ramps up to this point by adding fuel to the pilot tune stage (at the end of Mode 2), where upon transfer to Mode 3, the fuel added via the pilot tune stage is then transferred to the first portion of main fuel injectors. This ensures an efficient and quiet transfer into Mode 3. Fuel can be supplied to the first portion of the main injectors beginning at light-off and through approximately the 10% load condition. A depiction of the Mode 3 operation of the combustion system is shown in both FIGS. **6C** and **7C** where the main combustion flame established in Mode 3 is located radially outward of the fuel-air mixture from the pilot tune stage of injectors.

**[0046]** In a step **512**, the combustion system operates in a Mode 4, where fuel is supplied to a second portion of the main fuel injectors as well as to the first portion of the main fuel injectors, the pilot fuel nozzle and the pilot tune stage of injectors. Thus, in Mode 4 of operation, fuel is flowing through all four circuits of the combustion system and is now flowing to all of the main fuel injectors. As a result, a 360 degree ring of fuel is injected into the passing air flow from the main fuel injectors and radially outward of the combustion liner. In a step **514**, the fuel injected by the second portion of the main fuel injectors is ignited due to the main combustion flame established by the fuel injected from the first portion of main fuel injectors. This is the Mode 4 operation. Fuel can be injected through the second portion of the main fuel injectors beginning at light-off through approximately the 25% load condition. Fuel continues to flow through these circuits to approximately a 100% load condition, or what is also referred to as a baseload condition. Operation in Mode 4 provides a wide and stable operating range for the combustion system. A depiction of the Mode 4 operation of the combustion system is shown in both FIGS. **6D** and **7D** where the main combustion flame is enhanced by the fuel injection in Mode 4 and extends circumferentially about the pilot flame.

**[0047]** Once the combustion system has reached a baseload or 100% load condition, with fuel flowing through all four circuits, it is possible to modulate the fuel flow to one or more of the circuits supplying fuel to the core of the combustor, that is a modulated pilot fuel nozzle flow **360** and/or a modulated flow to the pilot tune stage **362**, as shown in FIG. **6E**. Reducing the amount of fuel is desirable when a lower load is demanded. However, traditionally, where fuel flow levels are reduced, flame temperature tends to decrease, which results in a corresponding rise in CO emissions. For example, referring back to FIG. **5**, in a step **516**, the fuel flow to the core injection region, that is the pilot fuel nozzle and/or the pilot tune stage injectors, can be adjusted. However, by maintaining the fuel flow to both the first portion and second portion of the main fuel injectors while modulating the fuel flow to the pilot fuel nozzle and/or the pilot tune stage of injectors, as depicted in FIG. **6E**, the main combustion flame remains in a complete ring and at a hotter temperature than the pilot flame. Thus, the hotter main combustion flame will consume the CO

generated by the colder pilot flame. This modulation of Mode 4 is depicted in FIG. **6E** and occurs during a normal premix operation of the combustion system.

**[0048]** As one skilled in the art will understand, when the power being demanded from the engine is reduced or turned down, it is desirable to effectively reduce the engine output while still maintaining operation of the engine. When less power is demanded of the engine, less fuel is necessary in the combustion process. Therefore, to turndown the engine, fuel flow must also be reduced. However, as discussed above, when fuel flow levels are reduced, flame temperature tends to decrease, which results in a rise in CO emissions. Therefore, it is necessary to adequately burn off this additional CO in order to keep the engine within emissions regulations. One way to burn off the CO emissions is to keep the main combustion flame generated by the first portion and second portion of the main fuel injectors as hot as possible. This can be accomplished through careful modulation of the fuel flow to the fuel injectors. More specifically, the fuel flow to the core region (pilot fuel nozzle and/or pilot tune stage injectors) is reduced, the fuel flow to the first portion and second portion of the main stage injectors is increased slightly. The net overall effect is a lower total fuel flow rate to the combustor, but a higher ratio of fuel being directed to support the main flame than the pilot and/or pilot tune stage, as fuel flow to the pilot region either decreases or is extinguished.

**[0049]** Although the steps of supplying the fuel flow and ignition of the injected fuel are discussed sequentially, one skilled in the art will understand that in order to maintain the flame that results from ignition of the fuel that has just been injected, the fuel flow must continue or the resulting flame will extinguish. Thus, it is necessary for the steps of fuel supply/injection to occur both prior to and simultaneous with the ignition of the fuel.

**[0050]** In an alternate embodiment of the present invention, the combustion system **300** comprises the four main fuel circuits for providing fuel to a pilot fuel nozzle, a set of pilot tune injectors and two circuits to the Main1 and Main2 flames forming a main combustion flame, as discussed above. However, it has been determined that combustion noise and emissions improvements can be achieved utilizing the present hardware without initially directing fuel to only the pilot fuel nozzle, but instead fueling both the pilot fuel nozzle and the set of pilot tune stage injectors to achieve initial light-off.

**[0051]** Referring to FIG. **8**, the alternate process for operating the gas turbine combustor is disclosed in process **800**. In a step **802**, fuel is initially supplied to a pilot fuel nozzle and a set of pilot tune stage injectors of the gas turbine combustor. Then, in a step **804**, the fuel injected by the pilot fuel nozzle and pilot tune stage injectors is ignited. Once a flame is established in the pilot region, fueling of the pilot fuel nozzle and the stage of pilot tune injectors continues through approximately a 10% load condition. Then in a step **806**, fuel is supplied to a first portion of a set of main fuel injectors. As discussed above, the first portion of the set of main fuel injectors consists of an approximately 120 degree arc-shaped section of fuel injectors. Fuel continues to flow to the pilot fuel nozzle and the pilot tune stage while fuel is being supplied to the first portion of the set of main fuel injectors. In a step **808**, the fuel injected by the first portion of the set of main fuel injectors ignites to form a main combustion flame. The fuel injected by the first portion of the main fuel injectors can begin as early as lightoff through approximately 10% load condition. Once the main combustion flame is established,



then in a step **810**, fuel is then supplied to a second portion of the set of main fuel injectors, while continuing to supply fuel to the first portion of the set of main injectors, the pilot fuel nozzle, and the pilot tune stage injectors. Fuel can be supplied to the second portion of the main fuel injectors beginning at light-off and approximately a 25% load condition. Then, in a step **812**, the fuel injected by the second portion of the set of main fuel injectors is ignited in order to enhance the main combustion flame. As with the other embodiment discussed above, in a step **814**, the fuel flow to the pilot tune stage injectors and pilot fuel nozzle can then be modulated in order to enhance the flame stability.

**[0052]** In yet another embodiment of the present invention, a method of operating a gas turbine combustor has been developed where fuel is supplied to three circuits and not a pilot tune stage of injectors, as previously discussed. Referring now to FIG. 9, the method **900** of operating the gas turbine combustor comprises a step **902** of supplying fuel to a pilot fuel nozzle of the gas turbine combustor. Then, in a step **904**, the fuel injected by the pilot fuel nozzle is ignited to form a pilot flame. In a step **906**, fuel is supplied to a first portion of a set of main fuel injectors while continuing to fuel the pilot fuel nozzle. Fuel can be supplied to the first portion of the main fuel injectors beginning at light-off and approximately a 10% load condition. Then, in a step **908**, the fuel from the first portion of main injectors is ignited to form a main combustion flame.

**[0053]** In a step **910**, fuel is supplied to a second portion of the set of main fuel injectors while also being supplied to the first portion of the main fuel injectors and the pilot fuel nozzle. Fuel can be supplied to the second portion of the main injectors beginning between light-off and approximately a 25% load condition. In one such embodiment of the present invention, the first portion of main injectors extend about approximately 120 degrees, in an arc-shaped path, while the second portion of the main injectors extend approximately 240 degrees of an arc-shaped path. In a step **912**, the fuel supplied to the combustor by the second portion of main injectors is ignited and serves to enhance the main combustion flame. As discussed above, fuel continues to flow through these various circuits up to approximately 100% load. Depending on the operating conditions of the engine, the process can continue in a step **914** where fuel flow to the pilot nozzle can be modulated. As discussed above, this modulation can include reducing the amount of fuel flow to the pilot fuel nozzle in order to support engine turndown while controlling CO emissions.

**[0054]** As one skilled in the art will appreciate, the present invention may be embodied as, among other things a method, system, or computer-program product. Accordingly, the embodiments may take the form of a hardware embodiment, a software embodiment, or an embodiment combining software and hardware. In one embodiment, the present invention takes the form of a computerized method, such as a computer-program product that includes computer-useable instructions embodied on one or more computer-readable media.

**[0055]** Computer-readable media include both volatile and nonvolatile media, removable and nonremovable media, and contemplates media readable by a database, a switch, and various other network devices. Network switches, routers, and related components are conventional in nature, as are means of communicating with the same. By way of example, and not limitation, computer-readable media comprise computer-storage media and communications media.

**[0056]** Computer-storage media, or machine-readable media, include media implemented in any method or technology for storing information. Examples of stored information include computer-useable instructions, data structures, program modules, and other data representations. Computer-storage media include, but are not limited to RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile discs (DVD), holographic media or other optical disc storage, magnetic cassettes, magnetic tape, magnetic disk storage, and other magnetic storage devices. These memory components can store data momentarily, temporarily, or permanently.

**[0057]** Communications media typically store computer-useable instructions—including data structures and program modules—in a modulated data signal. The term “modulated data signal” refers to a propagated signal that has one or more of its characteristics set or changed to encode information in the signal. An exemplary modulated data signal includes a carrier wave or other transport mechanism. Communications media include any information-delivery media. By way of example but not limitation, communications media include wired media, such as a wired network or direct-wired connection, and wireless media such as acoustic, infrared, radio, microwave, spread-spectrum, and other wireless media technologies. Combinations of the above are included within the scope of computer-readable media.

**[0058]** It is within the scope of this invention that the computerized method may be a stand-alone software program stored on its own piece of hardware that can be integrated within the operating system of the gas turbine engine or can be a software program that is designed to be integrated into existing software governing the operating system of the gas turbine engine.

**[0059]** While the invention has been described in what is known as presently the preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment but, on the contrary, is intended to cover various modifications and equivalent arrangements within the scope of the following claims. The present invention has been described in relation to particular embodiments, which are intended in all respects to be illustrative rather than restrictive. Alternative embodiments and required operations, such as machining of shroud faces other than the hardface surfaces and operation-induced wear of the hardfaces, will become apparent to those of ordinary skill in the art to which the present invention pertains without departing from its scope.

**[0060]** From the foregoing, it will be seen that this invention is one well adapted to attain all the ends and objects set forth above, together with other advantages which are obvious and inherent to the system and method. It will be understood that certain features and sub-combinations are of utility and may be employed without reference to other features and sub-combinations. This is contemplated by and within the scope of the claims.

1. A method of operating a gas turbine combustor comprising:

supplying fuel to a pilot fuel nozzle of the gas turbine combustor;

igniting the fuel injected by the pilot fuel nozzle;

supplying fuel to a set of pilot tune stage injectors and the pilot fuel nozzle, the pilot tune stage injectors positioned radially outward of the pilot fuel nozzle;



- supplying fuel to a first portion of a set of main fuel injectors, the pilot fuel nozzle and the pilot tune stage injectors;
- igniting the fuel injected by the first portion of the set of main fuel injectors to form a main combustion flame;
- supplying fuel to a second portion of the set of main fuel injectors, the first portion of the set of main injectors, the pilot fuel nozzle and the pilot tune stage injectors; and
- igniting the fuel injected by the second portion of the set of main fuel injectors to enhance the main combustion flame.
2. The method of claim 1 further comprising modulating the fuel to the pilot fuel nozzle and/or the pilot tune stage injectors.
3. The method of claim 1, wherein fuel is supplied only to the pilot fuel nozzle during lightoff of the gas turbine combustor and up to a full speed no load (FSNL) condition.
4. The method of claim 3, wherein fuel is supplied to the pilot tune stage injectors from light-off to approximately a 10% load condition.
5. The method of claim 4, wherein fuel is supplied to the first portion of the main injectors beginning at light-off to approximately the 10% load condition.
6. The method of claim 5, wherein fuel is supplied to the second portion of the main fuel injectors beginning at light-off to approximately a 25% load condition.
7. The method of claim 1, wherein the first portion of the set of main fuel injectors comprises an arc-like segment of fuel injectors spanning approximately 120 degrees and the second portion of the set of main fuel injectors comprises an arc-like segment of fuel injectors spanning approximately 240 degrees.
8. A computerized method, implemented by a processing unit, for staging fuel in a gas turbine combustor where the gas turbine combustor has a pilot fuel nozzle, a set of pilot tune stage injectors for tuning the pilot fuel nozzle and a main set of fuel injectors, the method comprising:
- operating the combustor in a first mode in which fuel is injected by the pilot fuel nozzle;
  - operating the combustor in a second mode in which fuel is injected by the pilot fuel nozzle and the injectors for the pilot tune stage;
  - operating the combustor in a third mode in which fuel is injected by the pilot fuel nozzle, the injectors for the pilot tune stage, and a first portion of the main set of fuel injectors; and
  - operating the combustor in a fourth mode in which fuel is injected by the pilot fuel nozzle, the injectors for the pilot tune stage, the first portion of the main set of fuel injectors and a second portion of the main set of fuel injectors.
9. The method of claim 8, wherein the first portion of the main set of fuel injectors extend across an arc-like span of approximately 120 degrees and the second portion of the main set of fuel injectors extend across an arc-like span of approximately 240 degrees.
10. The method of claim 8, wherein the first mode provides a pilot flame to the gas turbine combustor.
11. The method of claim 10, wherein fuel injected by the pilot tune stage provides an additional fuel source for modulating and supporting the pilot flame.

12. The method of claim 8, wherein fuel injected by the third mode and fourth mode is injected in an axially upstream direction and undergoes a reversal of direction prior to ignition.

13. The method of claim 8, wherein the fuel flow to the pilot fuel nozzle and the injectors of the pilot tune stage is adjustable after operating the combustor in the fourth mode.

14. A method of improving turndown capability of a gas turbine combustor while controlling carbon monoxide production from the gas turbine combustor comprising:

- modulating fuel flow to both a first portion and a second portion of an annular array of main fuel injectors supporting a main combustion flame; and
- modulating fuel flow to one or more fuel injectors in a core section of the gas turbine combustor.

15. The method of claim 14, wherein modulating fuel flow to both a first portion and a second portion of an annular array of main injectors comprises increasing the fuel flow to both the first portion and second portion.

16. The method of claim 15, wherein modulating fuel flow to one or more fuel injectors in a core section comprises decreasing the fuel flow to at least the pilot fuel nozzle.

17. The method of claim 16, wherein a ratio of fuel flow to main fuel injectors compared to the fuel flow to at least the pilot nozzle increases while total fuel flow to the engine decreases.

18. The method of claim 14, wherein the first portion comprises an annular array of main fuel injectors extending approximately 120 degrees and the second portion comprises an annular array of main fuel injectors extending approximately 240 degrees.

19. The method of claim 14, wherein the core section of the gas turbine combustor comprises a pilot fuel nozzle and injectors of a pilot tune stage, where the pilot tune stage of fuel injectors provide a fuel flow to support the pilot flame.

20. A method of operating a gas turbine combustor comprising:

- supplying fuel to a pilot fuel nozzle and a set of pilot tune stage injectors of the gas turbine combustor;
- igniting the fuel injected by the pilot fuel nozzle and the pilot tune stage injectors;
- supplying fuel to a first portion of a set of main fuel injectors, the pilot fuel nozzle, and the pilot tune stage injectors;
- igniting the fuel injected by the first portion of the set of main fuel injectors to form a main combustion flame;
- supplying fuel to a second portion of the set of main fuel injectors, the first portion of the set of main injectors, the pilot fuel nozzle, and the pilot tune stage injectors; and
- igniting the fuel injected by the second portion of the set of main fuel injectors to enhance the main combustion flame.

21. The method of claim 20 further comprising modulating the fuel to the pilot fuel nozzle and/or the pilot tune stage injectors for improving stability to the main combustion flame.

22. The method of claim 20, wherein fuel is supplied only to the pilot fuel nozzle and pilot tune stage injectors during lightoff of the gas turbine combustor and up to approximately a 10% load condition.

23. The method of claim 22, wherein fuel is supplied to the first portion of the main injectors beginning at light-off to approximately the 10% load condition.

**24.** The method of claim **23**, wherein fuel is supplied to the second portion of the main fuel injectors beginning at light-off to approximately a 25% load condition.

**25.** The method of claim **20**, wherein the first portion of the set of main fuel injectors comprises an arc-like segment of fuel injectors spanning approximately 120 degrees and the second portion of the set of main fuel injectors also comprises an arc-like segment of fuel injectors spanning approximately 240 degrees.

**26.** A method of operating a gas turbine combustor comprising:

supplying fuel to a pilot fuel nozzle of the gas turbine combustor;

igniting the fuel injected by the pilot fuel nozzle;

supplying fuel to a first portion of a set of main fuel injectors and the pilot fuel nozzle;

igniting the fuel injected by the first portion of the set of main fuel injectors to form a main combustion flame;

supplying fuel to a second portion of the set of main fuel injectors, the first portion of the set of main injectors, and the pilot fuel nozzle; and

igniting the fuel injected by the second portion of the set of main fuel injectors to enhance the main combustion flame.

**27.** The method of claim **26** further comprising modulating the fuel to the pilot fuel nozzle.

**28.** The method of claim **26**, wherein fuel is supplied only to the pilot fuel nozzle and pilot tune stage injectors during lightoff of the gas turbine combustor and up to approximately a 10% load condition.

**29.** The method of claim **28**, wherein fuel is supplied to the first portion of the main injectors beginning at light-off to approximately the 10% load condition.

**30.** The method of claim **29**, wherein fuel is supplied to the second portion of the main fuel injectors beginning at light-off to approximately a 25% load condition.

**31.** The method of claim **26**, wherein the first portion of the set of main fuel injectors comprises an arc-like segment of fuel injectors spanning approximately 120 degrees and the second portion of the set of main fuel injectors also comprises an arc-like segment of fuel injectors spanning approximately 240 degrees.

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