March 10, 1959 C. H. BARNARD ET AL 2,876,727

METHOD OF OPERATION AND CONTROL SYSTEM FOR SUBMARINE STEAM PROPULSION UNIT

Filed Jan. 10, 1952 3 Sheets-Sheet 1

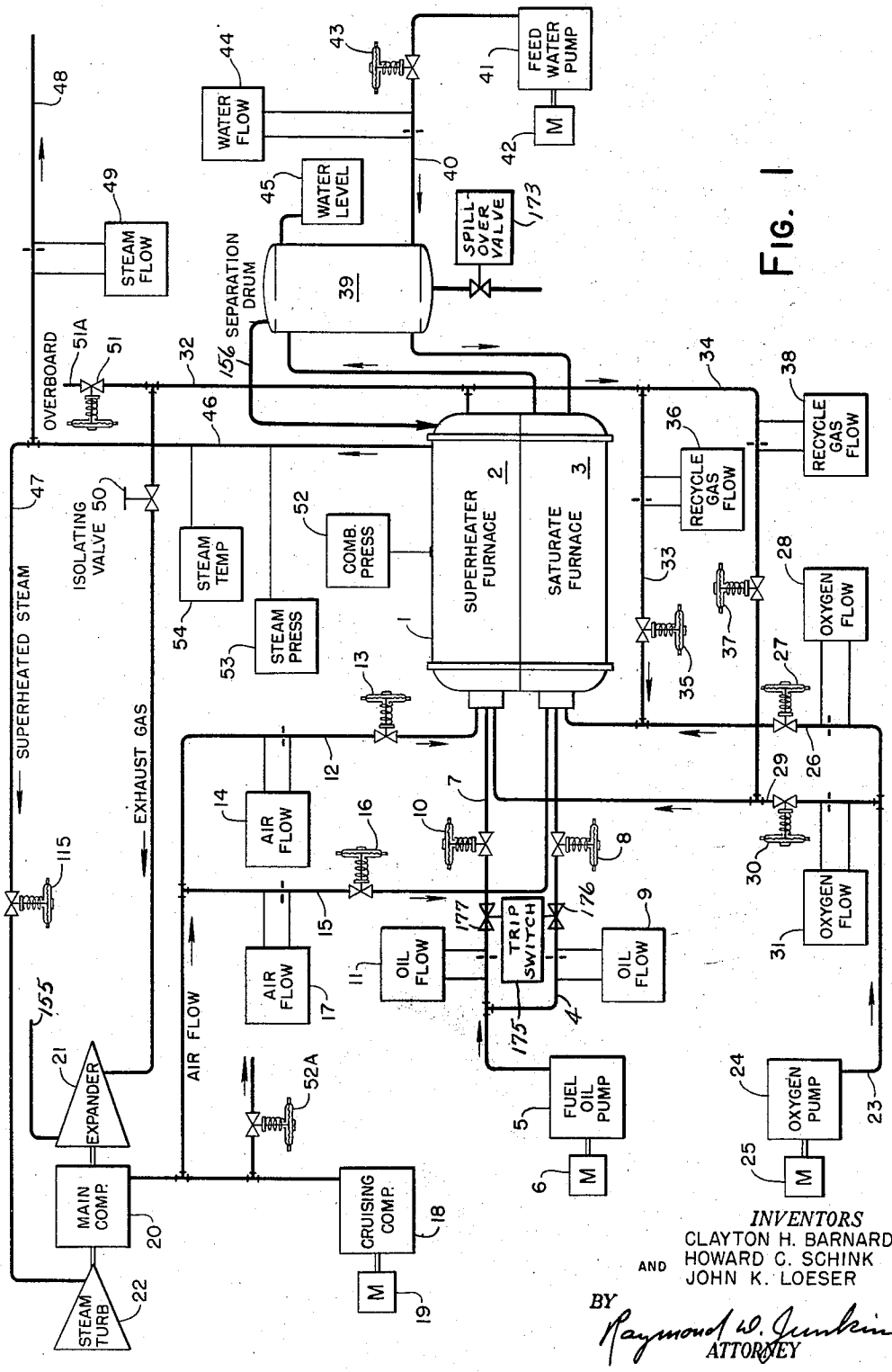


FIG. 1

INVENTORS
CLAYTON H. BARNARD
AND HOWARD C. SCHINK
JOHN K. LOESER

BY Raymond W. Junkins
ATTORNEY

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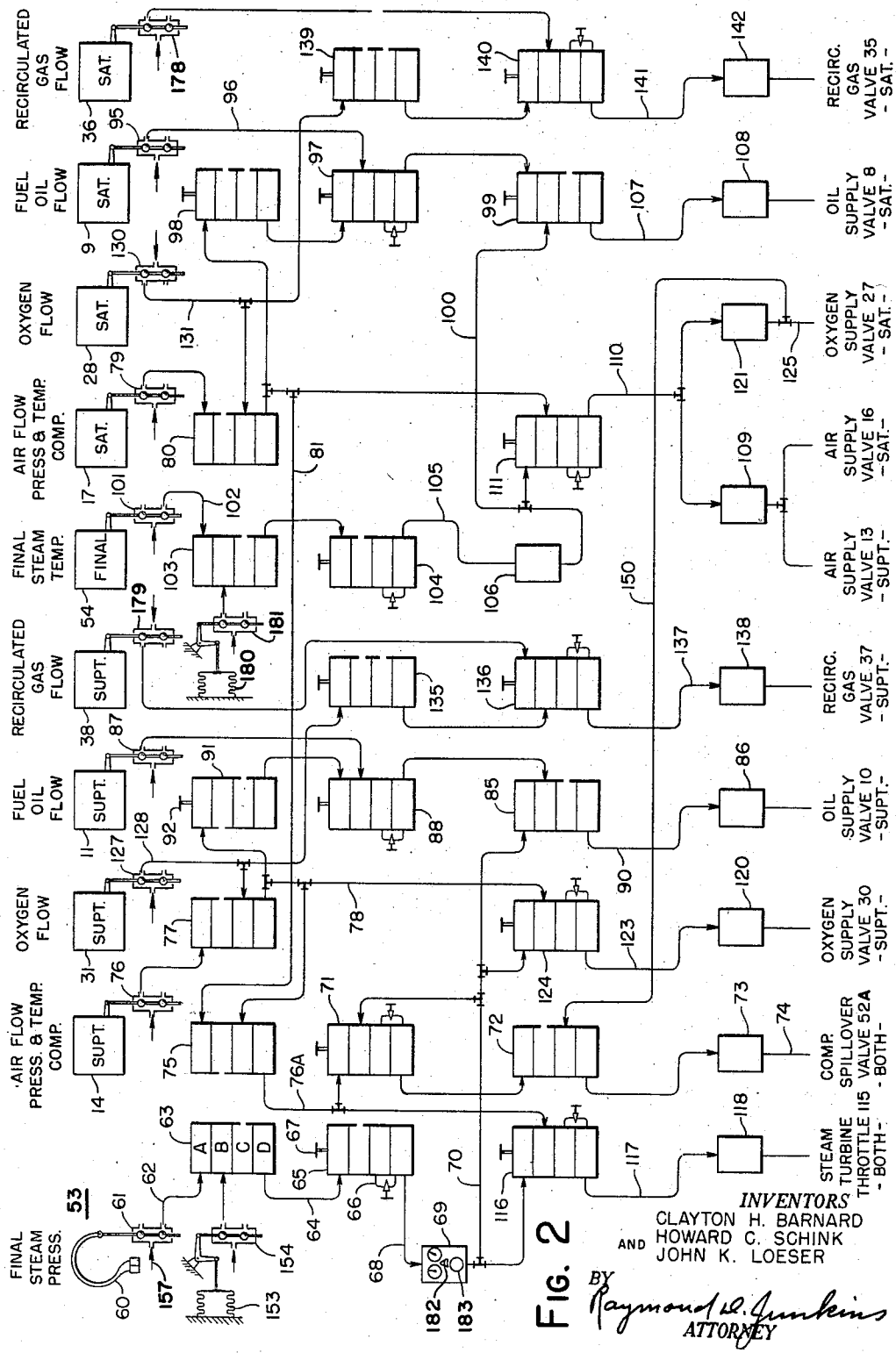


FIG. 2

INVENTORS
CLAYTON H. BARNARD
AND HOWARD C. SCHINK
JOHN K. LOESER

BY Raymond W. Gumkins
ATTORNEY

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Filed Jan. 10, 1952 3 Sheets-Sheet 3

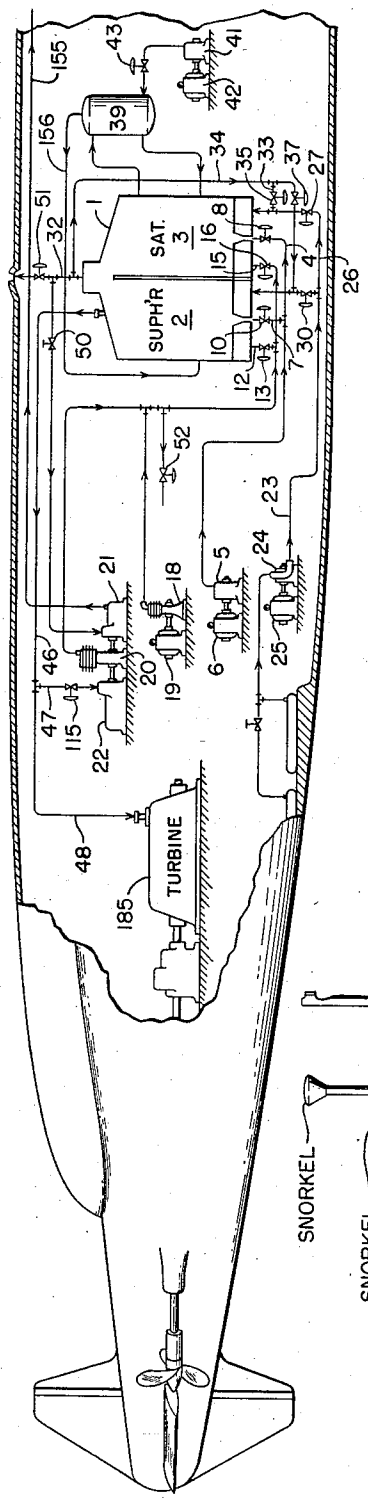


FIG. 3

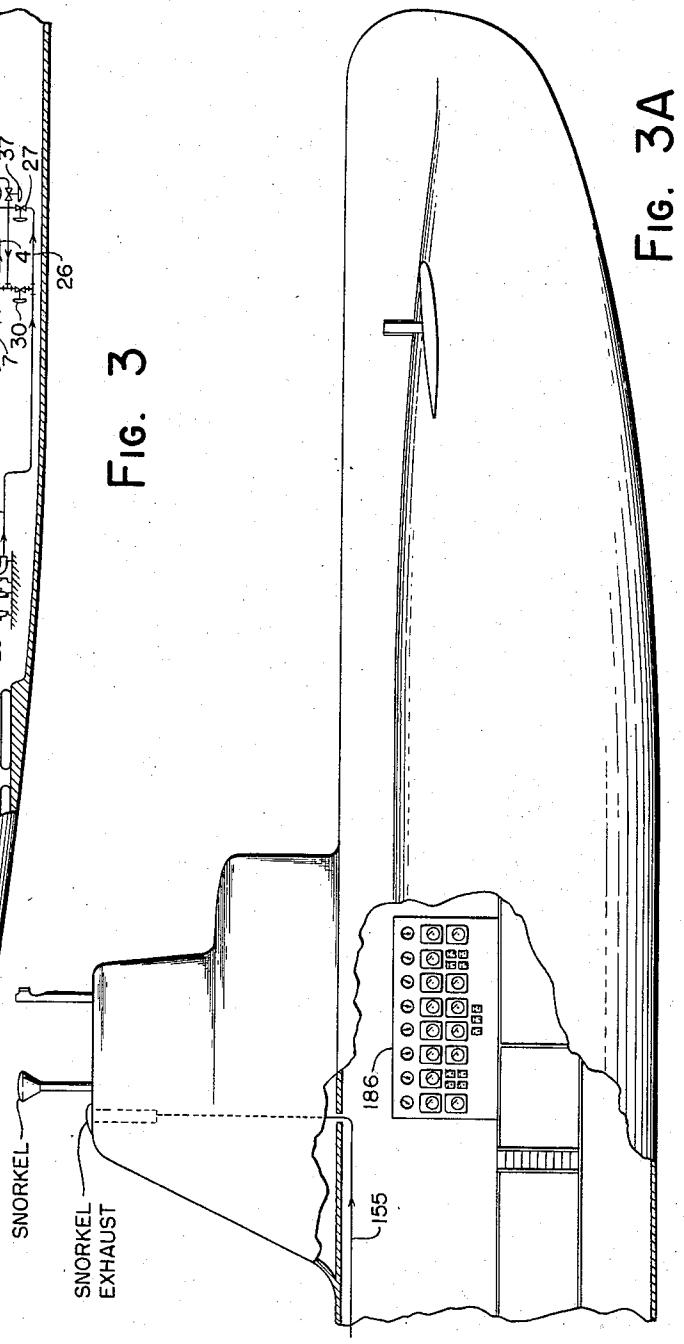


FIG. 3A

INVENTORS
CLAYTON H. BARNARD
AND HOWARD C. SCHINK
JOHN K. LOESER

BY Raymond W. Jumbein
ATTORNEY

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2,876,727

METHOD OF OPERATION AND CONTROL SYSTEM FOR SUBMARINE STEAM PROPULSION UNIT

Clayton H. Barnard, South Euclid, Howard C. Schink, Cleveland Heights, and John K. Loeser, Cleveland, Ohio, assignors to Bailey Meter Company, a corporation of Delaware

Application January 10, 1952, Serial No. 265,898

9 Claims. (Cl. 114—16)

This invention relates to control systems and apparatus for steam-powered submarine propulsion plants equipped with boilers having pressurized furnaces. Oil is the fuel to be burned preferably, although any fuel burned in suspension such as pulverized coal or gas may equally as well be utilized in connection with our invention. Under surface or snorkel operating conditions, air for combustion is to be furnished by means of centrifugal compressors, while under submerged operation liquid oxygen will be pressurized, heated to normal temperature, vaporized under pressure and supplied to the furnace for combustion.

It will be understood that a snorkel is a breathing device used by a submarine and may include a tube or a pair of tubes housing air intake as well as air and gas exhaust pipes which can be extended above the surface of the water for allowing operation with furnace or engine when the submarine is submerged. The arrangement allows discharge of exhaust air and gases at all times without entry of water when waves submerge the exhaust port. The inlet port allows air entrance when not covered by a wave but closes against water entry when the port is submerged by a wave.

The particular vapor generator to which the present invention is applied is known as a two-furnace boiler in order to provide wide range control of steam temperature. This boiler operates with forced water circulation under all conditions. One of the furnaces will be spoken of as the saturate furnace, while the other will be spoken of as the superheater furnace. By this we means that the saturate furnace is a separately fired furnace primarily vaporizing water into steam at saturated conditions of pressure and temperature, while the superheater furnace is separately fired for superheating the steam produced by the saturate furnace.

Fuel and oxidant supplied to the superheater furnace are controlled primarily from steam pressure in parallel with the saturate furnace. With this method of control the firing rate of the superheater furnace remains proportional to the saturate furnace and satisfies steam demand. To insure a constant steam temperature at the desired value, fuel and oxidant to the saturate furnace are continually readjusted as required by the temperature controller.

When using gaseous oxygen for supporting combustion, exit products of combustion will be recirculated to dilute the gaseous oxygen and thus to limit the furnace temperature.

During submerged operation furnace pressure is necessarily held high enough to permit the exit gases to be discharged overboard against the submergence pressure then existing.

A principal object of our present invention is to provide method and apparatus for controlling the operation of such a steam generating and superheating plant operating under surface, snorkel, or submerged conditions.

Another object is to provide an automatic control system of the fluid pressure actuated type for a steam-powered submarine propulsion plant.

Other objects will become evident from a study of the drawing and of the description thereof, as well as of the claims appended hereto.

In the drawings:

Fig. 1 is a diagrammatic showing of a steampowered submarine propulsion plant to which our invention has been applied.

Fig. 2 is a schematic showing of the measuring and controlling instrumentalities of Fig. 1.

Figs. 3 and 3A illustrate a submarine, in side elevation, with a portion of the hull broken away to disclose a diagrammatic showing of the vapor generator, propulsion equipment, auxiliaries, control panel, and principal interconnecting piping.

The showing of the drawing is quite diagrammatic and not to any scale. The same numbers are used to designate like parts on the sheets.

A steam generating and superheating structure **1** is shown as having a pressurized superheater furnace **2** and a pressurized saturate furnace **3**. The saturate furnace **3** is supplied with fuel oil through a conduit **4** by means of a pump **5** driven by a constant speed electric motor **6**. Fuel oil to the superheater furnace **2** is supplied through a conduit **7** from the pump **5**. Regulation of the rate of supply of fuel oil in the conduit **4** is had through the agency of a diaphragm actuated control valve **8**; while the rate of flow is continuously measured by a flow meter **9**. Similarly the flow of fuel oil to the superheater furnace **2** is regulated by a diaphragm actuated valve **10** and is measured by a flow rate meter **11**.

Air to support combustion in the superheater furnace **2** is supplied by way of a conduit **12** under regulation of valve **13** and measured by a flow meter **14**. Similarly air to the saturate furnace **3** is supplied through a conduit **15**, regulated by a valve **16**, and measured by a flow meter **17**. The conduits **12** and **15** are connected to a cruising compressor **18** driven (when operating) by a constant speed electric motor **19**. Also connected to the air supply conduits **12, 15** is a main compressor **20** which is driven (when operating) by an exhaust gas expander **21** and a steam turbine **22**. When the main compressor **20** is in operation approximately 30 percent of its driving power is supplied by the expander **21** and the remaining 70 percent of power by the steam turbine **22**.

Under certain conditions of operation, to be explained hereinafter, oxygen to support combustion is supplied to the two furnaces through a conduit **23** by an oxygen pump **24** driven by a variable speed electric motor **25**. The showing is quite diagrammatic and omits the equipment for gasification of liquid oxygen and the two stages of gaseous oxygen pressure control. The conduit **23** branches as at **26** to the saturate furnace **3** and the branch **26** has an oxygen flow regulating valve **27** and a flow meter **28**. A second branch **29** supplies the superheater furnace **2** and **29** has a regulating valve **30** and flow meter **31**.

Under certain conditions of operation all of the exhaust products of combustion from the two furnaces pass through a conduit **32** to the expander **21**, whereas, under other conditions of operation, a portion of the products of combustion are diverted through a branch conduit **33** which joins the oxygen supply conduit **26** while a further branch **34** joins the oxygen supply conduit **29** on the furnace side of regulating valves **27** and **30** respectively. The branch **33** is provided with a regulating valve **35** and a flow meter **36**, while the branch **34** is provided with a regulating valve **37** and a flow meter **38**.

A separation drum **39** is connected to the fluid circuits of the unit and is supplied with feed water through a conduit **40** by means of a pump **41** driven by a motor **42**. Supply rate through the conduit **40** is under the control of a diaphragm actuated regulating valve **43** and is con-

tinuously measured by a rate of flow meter **44**. A water level measuring device **45** is continuously sensitive to liquid level within the drum **39** for a purpose to be explained hereinafter. The steam separated in the drum is taken to the superheater furnace **2** by conduit **156**.

Superheated steam leaves the unit through a conduit **46** which branches as at **47** to supply the steam turbine **22** when it is operating. The principal output of the power system, namely superheated steam, leaves through a conduit **48** and is measured by a rate of flow meter **49**. The conduit **48** supplies superheated steam to one or more main propulsion turbines **185**.

The exhaust gas conduit **32**, leading to the expander **21**, is provided with a hand actuated isolating valve **50**. On the furnace side of the valve is an overboard valve **51** for discharging exhaust products of combustion overboard under the control of a combustion pressure regulator **52**.

There are certain basic requirements to be met in the operation of such a power plant. The rate of combustion must be controlled to satisfy steam demand. Fuel should be proportioned to oxidant when using air during surface or snorkel operation, or when using oxygen during submergence. A proportioning control is provided capable of supplying sufficient oxygen for efficient combustion of the fuel oil. Control of feed water supply will proportion the water inflow in accordance with requirements, and a spill-over valve from the drum to the main condenser provides against excessively high drum levels during maneuvering operations. When using gaseous oxygen for combustion, exit gases will be recirculated to limit furnace temperature. During submerged operation, furnace pressure will be maintained high enough to permit the exit gases to be discharged overboard against the submergence pressure then existing.

With this divided furnace unit, control is accomplished by adjusting the firing rate to each furnace individually. The firing rate to the superheater furnace is adjusted in accordance with steam pressure which serves as an indication of load demand. Firing rate of the saturate furnace is adjusted in accordance with the requirements of superheated steam temperature which is measured at the superheater outlet. An increase in boiler load therefore results in an increase in firing rate in both the superheater and saturate furnaces. During surface or snorkel operation, air flow supplied to the units for the combustion of fuel oil will be furnished by either the cruising or the main air compressor depending on the plant load.

When operating with the cruising compressor, control of combustion air is accomplished by opening the compressor spill-over valve **52A**, thus wasting air not required for combustion to the hull interior.

Fuel and air to the superheater furnace are controlled primarily by steam pressure. The steam pressure controller **53** measures steam pressure at the superheater outlet in conduit **46** and develops an air loading pressure proportional thereto. Since steam pressure is a measurement of balance between heat input in the form of fuel and oxidant, and heat output in the form of steam, any change in steam demand upon the unit causes pressure to begin to change at a corresponding rate, with a similar change in loading pressure from the controller. This change in loading pressure acts to continuously adjust the quantities of fuel and oxygen to the superheater furnace to fill the requirements of the new load condition as indicated by the return of steam pressure to a preset value.

Fuel and oxidant to the saturate furnace are controlled primarily from steam temperature. A steam temperature controller **54** measures steam temperature at the superheater outlet and develops an air loading pressure proportional to this measurement. As in the case of steam pressure control, a change in steam temperature is accompanied by a corresponding change in loading pressure, which causes fuel and oxidant to be adjusted until the preset temperature is reestablished at the new load condition.

This method of controlling the superheater furnace from pressure and the saturate furnace from temperature is unusual in that it is the reverse of what might ordinarily be expected but this system is necessary in order to maintain steam pressure control at low boiler loads when the superheater furnace only will be fired. While a decrease in steam pressure will act to increase firing rate to the superheater furnace it should be noted that a corresponding decrease in temperature will decrease firing rate in the saturate furnace.

The boiler plant will function under three phases of operation; surface, snorkel and submerged. The first two modes of operation will utilize air from either the cruising or the main compressor, depending upon load requirements. During submerged operation, liquid oxygen will be evaporated and supplied to the furnace in gaseous form under pressure.

Surface operation—light loads

The cruising compressor **18** will be used to supply air for combustion during periods of light load operation. Since this unit is driven by a constant speed direct current motor **19**, control of the amount of combustion air supplied to the two furnaces is obtained by throttling a compressor spill-over valve **52A** which wastes (to the hull) the air not required for combustion. Control of the quantity of fuel oil fired is accomplished by adjusting a stroke operator on pump **5** and regulating burner control valves **8** and **10**.

The steam pressure measuring-transmitter **53** (Fig. 2) includes a Bourdon tube **60** and pneumatic pilot valve **61**. The pilot valve assembly **61** is of the type disclosed and claimed in the Johnson Patent 2,054,464. The arrow **157** represents a controlled air supply, usually at 30 p. s. i., through a pressure reducing valve from the plant source. The other similar pneumatic pilot valves of the drawing and specification each have an arrow indicating air supply from the same constant pressure source. It measures steam pressure in the superheater outlet header **46** and develops a proportional air pressure signal in a pipe **62** which joins the A chamber of an ambient pressure cutback relay **63** which may be of the general type described and claimed in Dickey Patent 2,098,913. The output pressure of relay **63**, available in chamber D, is subjected through a pipe **64** upon the A chamber of a ratio standardizing relay **65** which is of the type described and claimed in Gorrie Re. 21,804. Relay **65** provides a proportional control with reset characteristics. It provides for the demand index (final steam pressure), a floating control of high sensitivity superimposed upon a positioning control of relatively low sensitivity. The function of the adjustable bleed **66**, between the C and D chambers of the relay, is to supplement the primary control of the pressure effective in pipe **64** with a secondary control of the same or of different magnitude as a follow-up or supplemental action to prevent over-travel and hunting. The relay **65** is also provided with ratio adjusting means illustrated as a hand knob **67**.

When we speak of "ambient" pressure or temperature we mean the pressure or temperature "ambient to" or "adjacent" the particular apparatus under discussion and within the hull or other confined space in which the apparatus is located. It is intended to mean the pressure or temperature within the submarine hull, airplane body, or other confined space containing the controlling instrumentalities and/or the controlled devices. In the present submarine embodiment it might be termed "hull interior" pressure or temperature.

The output signal of relay **65**, available in a pipe **68**, is passed through a hand-automatic selector valve station **69** of the type described and claimed in the Fitch Patent 2,202,485 providing a possibility of selective remote hand or automatic operation. The selector station **69** is rep-

resentative of all of the manual-automatic selector stations of the present specification and drawing. It is provided with visual pressure gages, a manual-automatic selector knob 182 and a control knob 183. When the knob 182 is manually turned to "automatic" position then the knob 183 is inoperative and the loading pressure of pipe 68 is effective in pipe 70. When the knob 182 is in "manual" position the loading pressure of pipe 68 is blocked, and the pressure in pipe 70 is regulated by manual manipulation of control knob 183. The station 69, along with the other similar stations, is located on the central control panel 186 (Fig. 3A) where an operator has the choice of performing our claimed methods either automatically or remotely manually. The output signal from the selector station, whether by automatic means or hand adjustment, is available in a pipe 70 and acts through the various relays to adjust the supply rates of the elements of combustion to satisfy the demand for steam. Under cruising operation (light load) this acts through a control of the compressor spill-over valve 52A and the superheater furnace oil supply valve 10.

The master signal in pipe 70 is subjected upon the B chamber of a ratio standardizing relay 71, whose output acts through a computer relay 72 and selector station 73 to a pipe 74 joining the diaphragm chamber of the spill-over valve 52A. The relay 71 is used for the purpose of furnishing an air flow tie-back control. A change in steam pressure is represented by a change in loading pressure which functions through relays 63, 65, 71, and 72, to vary the degree of throttling of spill-over valve 52A; the resultant change in combustion air supplied to both furnaces is totalized by a relay 75 and its effect is balanced against the master air pressure signal in relay 71.

The air flow meter 14 is connected across an orifice in the conduit 12 which supplies air to the superheater furnace and the meter actuates the movable element of a pneumatic pilot 76 to thereby establish in the A chamber of a computer relay 77 an air control pressure continuously proportional to the amount of air being furnished to the superheater furnace 2. The output of relay 77, available in a pipe 78, is subjected upon the C chamber of relay 75. In similar fashion the air flow meter 17 is connected across an orifice in the pipe 15 supplying air for combustion to the saturate furnace 3 and positions the movable element of a pneumatic pilot 79 to thereby establish in the A chamber of a computer relay 80 an air pressure continuously proportional to the amount of air being furnished to the saturate furnace 3. The output of relay 80, available in a pipe 81, is subjected upon the A chamber of relay 75. The totalizing relay 75 algebraically adds the pressures proportional to the two air flow supply rates and the output of relay 75, available in pipe 76A, is subjected upon the A chamber of relay 71 to balance against the master steam pressure signal of the B chamber. Thus the relay 71 continuously checks the master demand for air flow against the actual measured air flow and provides a readjusting effect upon the spill-over valve 52A if necessary.

Control of fuel oil supply rate to the superheater furnace is accomplished through a computer relay 85 which balances the master signal (pipe 70 to A chamber of relay 85) against a signal (in B chamber of relay 85) originating from a fuel oil flow meter 11 previously mentioned. Primary control of the oil flow is accomplished in parallel with air flow; that is, the air pressure signal from the steam pressure selector 69 in addition to adjusting air flow also acts through the relay 85 and selector 86 to position the oil control valve 10.

The fuel oil flow meter 11 is sensitive to the pressure differential produced by fuel oil flow through an orifice located in oil supply conduit 7; and positions the movable element of a pilot 87 thereby establishing in the B chamber of a ratio standardizing relay 88 an air pressure signal continuously representative of fuel oil supply rate to the superheater furnace. The output of relay 88 is subjected upon the B chamber of the computer relay 85 in tie-back opposition or balance to the master steam pressure signal. If the pressures acting upon the relay 85 are not in balance, indicative of a need for change in fuel oil supply rate to this furnace, the unbalance is represented by a change in control pressure in pipe 90 which acts through the selector station 86 to readjust the throttling position of fuel oil valve 10.

In order to provide the possibility of manual adjustment of the ratio of fuel to air flow required, an oxidant ratio relay 91 is installed in the control circuit for this purpose. The input pressure to this relay, subjected upon the relay A chamber from pipe 78, is proportional to oxidant being supplied and by means of a knob 92 adjustment, the ratio of the output to input pressures may be adjusted. The output pressure of the relay 91 in turn acts upon the A chamber of relay 88 where it is balanced against the B chamber pressure proportional to oil flow. The output of relay 88 to computer relay 85 is therefore proportional to any deviation from the desired ratio of oil to combustion oxidant. While the primary changes on both the combustion air and the oil flow are made from the steam pressure controller 60, 61, deviations in the desired proportion of fuel oil to combustion air are corrected by variations in the air pressure signal from the ratio relay 88.

During this type of surface operation the hand isolating valve 50 is closed and all of the exhaust products of combustion from the two furnaces are discharged overboard by way of the pipe 32 through valve 51.

Fuel oil supply for the saturate furnace is measured by the flow meter 9 which is sensitive to the pressure differential existing across an orifice located in the supply line 4 and positions the movable element of a pneumatic pilot 95 to continuously establish in a pipe 96 a fluid loading pressure representative of rate of fuel oil supply to the saturate furnace. The loading pressure of the pipe 96 is subjected upon the B chamber of a ratio standardizing relay 97 which is similar to relay 88 for the superheater furnace. Measured air flow to the saturated furnace, as represented by a signal in the pipe 81, is subjected upon the A chamber of a ratio relay 98 which is similar to the relay 91. The output of relay 98 is subjected upon the A chamber of the relay 97 and the final output of relay 97 is subjected upon the A chamber of a ratio relay 99.

The relay 99 is similar in function to the relay 85 except that the relay 99 receives in its B chamber a signal from a pipe 100 originated by the steam temperature measuring device 54; whereas the relay 85 receives in its A chamber a signal from the master steam pressure controller.

The steam temperature measuring device 54 is arranged to position the movable element of a pneumatic pilot 101 to establish in a pipe 102 a fluid loading pressure continuously representative of final superheated steam temperature. The pipe 102 is joined to the A chamber of an ambient pressure cut-back relay 103 similar to the relay 63. The output of relay 103 joins the A chamber of a ratio standardizing relay 104 whose output, available in a pipe 105, passes through the selector station 106, to the pipe 100 previously mentioned.

Thus the control pipe 107, leading through a selector station 108, positions the saturate furnace oil supply valve 8, primarily under the dominance of steam temperature and secondarily having a check-back from measured fuel oil flow to the saturate furnace by means of the meter 9.

The control of air flow to this furnace is accomplished by an air pressure signal from selector station 109 which adjusts the control valves 13, 16 regulating combustion air to each furnace in such a manner as to change the distribution of the total air supplied as between the two furnaces. The selector 109 is joined by a signal pipe 110 which is the output of a ratio standardizing relay

111. The relay 111 receives in its A chamber a signal from pipe 100 representative of final steam temperature and in its B chamber a signal from pipe 81 which is representative of measured air flow to the saturate furnace. Thus, while the total air flow to both furnaces is controlled by the compressor spill-over valve 52A, the proportioning between the two furnaces is by way of valves 13, 16.

Combustion sensitive controller 52 of Fig. 1 is responsive to both the pressure within the pressurized combustion space, common to the superheater furnace 2 and the saturate furnace 3, as well as the submergence water head. The internal structure is obviously the elementary one of two pressure responsive members, each sensitive to one of these pressures, opposing their forces in positioning an air pilot valve which establishes a controlling pressure for the diaphragm of overboard discharge valve 51 in exhaust gas conduit 51A. Obviously the mechanical advantage of one pressure responsive member over the other in positioning the pilot valve can be given an arrangement whereby an adjustment would vary this advantage. Any one of the common expedients for terminating this automatic control and giving a manual control to the setting of valves 51 is available as demonstrated elsewhere in the specification and drawings.

Surface operation—heavier loads

For operation at greater than cruising load conditions, the main air compressor 20 is used as the source of combustion air. Control of the compressor 20 is accomplished by a steam turbine throttle valve 115 in steam conduit 47. The master steam pressure signal is impressed upon the A chamber of a ratio standardizing relay 116 whose output signal (in pipe 117) acts through a selector station 118 to position the throttle valve 115. Relay 116 serves as an air flow tie-back by having its B chamber loaded from total air flow through the pipe 76A output of the air flow totalizing relay 75. A change in air pressure signal from the master selector 69 will cause the main compressor 20 to continually change speed in one direction until the air pressure signal from the air flow relay 75, effective in the B chamber of relay 116, indicates that the required change in combustion air flow rate has been accomplished. During this phase of operation the compressor spill-over valve 52A remains in a closed position with all changes in combustion air rate being effected by varying the speed of the main air compressor. The transition from the cruising to the main compressor is made a semi-manual operation as it occurs rather infrequently and under preselected desire by the operator.

During this somewhat heavier load operation the exhaust products of combustion are utilized by way of expander 21 to provide about 30 percent of the power requirements of main compressor 20. The hand isolating valve 50 is opened and the controller 52 is hand adjusted to maintain valve 51 normally closed so that all of the products of combustion will pass through the expander.

Exhaust gases from the expander 21 leave through a conduit 155 to the snorkel exhaust (Fig. 3A). Under surface operation the snorkel exhaust freely passes the gases to the atmosphere. Under snorkel operation the intermittent or occasional wave submergence of the snorkel exhaust does not introduce sufficient back pressure, relative to expander discharge pressure, to disturb or pulsate air supply to conduits 12, 15 from the main compressor 20.

We have indicated in Fig. 2 that the air flow meters 14 and 17 are each provided with automatic compensators sensitive to ambient air pressure and temperature.

In order that air flow may be distributed in the correct proportions, a control valve is located in the air supply line to each furnace. The positions of both of these valves will be controlled in accordance with the requirements of the saturate furnace and in such a manner that the air flow will be distributed with total flow from the compressor remaining reasonably constant for any given compressor speed. This feature permits a minimum pressure loss through the control valves.

In addition to the primary control of fuel oil from pressure or temperature, a proportioning control is supplied for each furnace for the purpose of readjusting fuel oil in order to maintain the desired ratio of fuel oil to combustion air. This is accomplished by measuring fuel oil flow and the proportional quantity of oxygen in combustion air flowing to each furnace, and by means of the ratio controller, a definite proportion of fuel oil to combustion air is established. An air loading pressure proportional to change in the desired ratio acts through a standardizing relay and totalizing relay to continuously correct fuel oil flow until the desired ratio as determined by the control set point has been established.

Submerged operation

During submerged operation it becomes necessary to use oxygen as the oxidant of combustion, and liquid oxygen is vaporized, pressure controlled, and diluted with recirculated products of combustion to limit furnace temperature. In addition to providing automatic control of steam pressure and steam temperature, the correct fuel-oxidant ratio, and drum liquid level; the system maintains the correct ratio of recycled exhaust gases to gaseous oxygen, and the desired furnace combustion pressure.

Under this operation the main compressor 20 is not used and the hand isolating valve 50 is closed. Selector station 118 is turned to "hand" and throttle valve 115 is remotely manually closed. Selector 118 thereafter isolates the valve 115 from pressure signals of pipe 70.

The control of gaseous oxygen flow is accomplished by varying the degree of throttling of the oxygen control valves 27, 30 through selector station 120 on the superheater side and 121 on the saturate side.

The control of gaseous oxygen flow, through selector station 120 from steam pressure and oxidant supply is accomplished in the same manner as when firing with the main compressor, with the exception that the control signal through selector 120, in pipe 123, is a result of comparing the steam pressure signal 70 with oxidant signal 78 in relay 124. At the same time the oxygen flow control valve 27 for the saturate furnace receives its regulating signal from a pipe 125, through selector 121, as a resultant from saturate furnace oxidant supply signal 81 and steam temperature signal 105, through relay 111. It will therefore be seen that the oxygen supply valve 30 for the superheater furnace is primarily controlled by the steam pressure signal in pipe 70 and with a tie-back from measured rate of oxygen flow through the pipe 78 signal. The oxygen gaseous flow to the saturate furnace is controlled by the valve 27 primarily from steam temperature signal in pipe 105 and with a tie-back from metered oxygen flow rate through signal in pipe 81.

The oxygen flow meter 31 for the superheater furnace is arranged to position the movable element of a pneumatic pilot 127 thus establishing in a pipe 128 a pneumatic loading pressure continuously representative of rate of gaseous oxygen flow to the superheater furnace. The pipe 128 joins the C chamber of the oxidant relay 77 whose output is available in the pipe 78 previously mentioned. The oxygen flow meter 28 for the saturate furnace is arranged to position the movable element of a pneumatic pilot 130 thereby establishing in a pipe 131 a control pressure signal continuously representative of rate of gaseous oxygen flow to the saturate furnace. Pipe 131 communicates with the C chamber of total oxidant relay 80 to produce a control pressure in pipe 81 previously mentioned.

The computer relay 77, previously sensitive to air flow supply rate to the superheater furnace is now sensitive to measured oxygen flow from pipe 128 and the out-

put of the relay, available in pipe 78, controls the oxygen valve 30 and the fuel oil supply valve 10. For the saturate furnace the computer relay 80, previously sensitive to air flow to the saturate furnace, is now sensitive to gaseous oxygen flow and the output of the relay 80, available in the pipe 81, positions the oxygen valve 27 and assists in positioning the oil supply valve 8 for the saturate furnace.

An oxygen ratio relay 135 determines the proportion of recirculated gas to be mixed with gaseous oxygen to dilute the latter for limiting furnace temperature. The ratio of recycled gas flow to gaseous oxygen before entering the superheated furnace is automatically maintained in the correct proportion by varying the position of the recycle gas control valve 37. This is accomplished through ratio standardizing relay 136 which receives air pressures proportional to recycled gas flow (from meter 38 and pilot 179) and pure oxygen flow and acts to develop an air pressure proportional to any deviations in the desired ratio. The oxygen ratio relay 135 provides manual selection of the desired ratio of recycled gas to oxygen. The output signal of the ratio relay 136, available in the pipe 137, is effective through selector 138 in positioning the superheater furnace recycle gas valve 37.

Control of this function on the saturate furnace is similar. A ratio relay 139 provides manual selection of the desired ratio of recycled gas to oxygen and its signal joins a ratio standardizing relay 140 which also receives a signal representative of measured recirculated gas flow to the saturate furnace by meter 36 and pilot valve 178. The output of the relay 140, available in a pipe 141, is effective through selector 142 to position the recycled gas valve 35 for the saturate furnace.

A measuring device sensitive to furnace temperature indicates same on the control panel 186 (Fig. 3A) available to the operator who may adjust the ratio knobs of relays 135 and 139 to regulate the ratio of recirculated gas flow to gaseous oxygen flow and thus maintain furnace temperature below an excessive value.

Under this mode of operation, with a portion of the products of combustion recirculated to dilute gaseous oxygen and thus to limit furnace temperature in each of the two furnaces, the remainder of the exit gases are discharged overboard through valve 51. Combustion chamber pressure must be maintained sufficiently high to discharge gases overboard against the depth of submergence. Oxygen gaseous supply is used to aspirate the recycled gas to the furnace. Combustion pressure control is accomplished by throttling valve 51 in overboard conduit 51A under the regulation of combustion pressure regulator 52.

Since the two furnaces have a common discharge, a single throttling valve 51 provides combustion pressure control. The pressure controller 52 measures combustion pressure at a point common to both furnaces and develops an air loading pressure proportional to this measurement. This loading pressure operates through the necessary relay to continuously adjust the position of the exhaust gas valve 51 to maintain combustion pressure at its set value.

Both the main compressor and the cruising compressor have characteristics such that flow and pressure rise and fall together. When it is desired to transfer from air burning (particularly from the main compressor) to oxygen firing, it will be seen that, as we begin to open oxygen valve 27 through hand manipulation of selector 121, the oxygen flow meter 28 will act through pipe 131, relay 80, pipe 81, relay 75, pipe 76A, relay 71 and relay 116 to indicate an excess of oxidant and tend to cut back on throttle 115. To prevent this and to maintain combustion chamber pressure we tie the output of selector 121, by way of a pipe 150, to relay 72 which controls the spill-over valve 52A to dump air without changing compressor speed.

For all three modes of operation the feed water control supplies the boiler in accordance with load demand. This is accomplished by metering superheated steam flow in the outlet header 48 with a flow rate meter 49 and metering feed water inflow rate through conduit 40 by flow meter 44. Air pressures proportional to steam outflow and water inflow are developed by these measuring controllers, and through a relay, develop an air pressure which positions the feed water control valve 43 to maintain the same rate of water inflow to the boiler as steam outflow therefrom. Deviations in separator drum (39) water level are sensed by measuring controller 45 which develops an air pressure proportional to water level and acts upon the relay to modify the steam flow-water flow control of valve 43 as may be necessary to maintain correct separator drum level. During rapid load swings, excessively high drum levels are prevented by opening a drum spill-over valve 173 from the air pressure developed by controller 45.

Snorkel operation

When firing the unit under snorkel conditions, changes in ambient pressure within the hull are expected although the depth of submergence is relatively constant. The ambient pressure cut-back relay 63 (and similarly the relay 103) has been included in the control system for the purpose of reducing firing rate (and consequent use of hull air) during periods of low hull pressure. This is accomplished by loading the B chamber of relay 63 with a loading pressure representative of hull interior pressure changes as sensed by a pressure member 153 positioning a pilot 154. Similarly a pressure member 180 positions the movable element of a pilot 181 to establish a loading pressure representative of hull interior pressure for subjection on the B chamber of relay 103. Thus the pressure signal in pipe 62 is modified by a pressure in proportion to changes in hull ambient pressure. This modified control signal (in pipe 64) acts to reduce firing rate whether operating under cruising or main air compressor, when the air for combustion is drawn from the hull interior. Were the firing rate not reduced (and the air withdrawal from the hull undiminished) during snorkel closure of some 8 seconds, the hull air would be exhausted to such an extent as to be dangerous to the personnel. Additionally a trip switch 175 measuring hull pressure has been included for the purpose of tripping out the fires by actuating valves 176 and 177 upon reaching a dangerously low hull pressure.

Referring specifically to Fig. 2 relays 65, 116, 71, 124, 88, 136, 104, 111, 97 and 140 have been designated as standardizing type relays. For use under ambient pressure changing conditions, such as might be encountered during snorkel operation, or under varying depth of submergence, it was found that this type of relay would tend to hold a constant absolute pressure following a sudden change rather than a constant gage pressure which is required of the system, and which the remainder of the components produced. To compensate for this, an additional bellows was added, together with a bleed valve, which will compensate for the reset rate bleed adjustment in such a way that the output during variable ambient pressure conditions will remain on a constant gage pressure basis. Details of this compensation are not shown in the present drawing and reference should be made to the copending application of Howard C. Schink, S. N. 318,308 filed November 1, 1952, now Patent 2,860,650, which is directed particularly to such an ambient pressure or barometric pressure compensated relay.

It will be seen that we have provided apparatus and a method of operation to handle a steam boiler plant for a submarine which will function under three definite phases of operation; surface, snorkel and submerged. The first two conditions of operation take air from the hull interior by way of either a cruising or main compressor, depending upon load requirements. During sub-

merged operation, liquid oxygen is evaporated and supplied to the boiler furnaces in gaseous form. Regardless of the method of operation, the automatic combustion control performs the following basic functions: maintaining steam pressure at the correct value, maintaining final steam temperature at the desired value, maintaining combustion pressure, maintaining the correct ratio of fuel to oxidant, and maintaining feed water supply rate as needed. Change-over from one method of firing to another is manual through remotely actuated instrumentalities and immediately following such a change-over, the automatic control system functions under the new mode of operation.

While we have described certain automatic methods and systems of operation, under different conditions of service, it will be apparent that our methods may be manually performed through observation of the various measuring instrumentalities and remote manual control of the controllable factors. In Fig. 3A we show a control control panel **186** upon which may be mounted various measuring devices of variables in the operation of the plant, for example, the meters **53, 14, 31, 11, 38, 54, 17, 28, 9** and **36** etc., as well as manual-automatic selector valves **69, 106, 118** etc. Some, or all, of the relays may also be mounted on the panel **186**, as well as controllers **52, 53** and **54**. The operator may observe the measuring instrumentalities and remotely manually operate the selector stations to perform the claimed methods.

It will be evident that, while we have chosen to illustrate and describe one preferred embodiment of our invention in connection with a submarine as exemplifying an enclosed space, we contemplate that our invention is equally as well adapted to enclosed spaces as, for example, the pressurized hulls of airplanes, the pressurized or evacuated containers of atomic piles, or the like.

What we claim as new, and desire to secure by Letters Patent of the United States, is:

1. The method of operating the steam generation process of a submarine propulsion unit having two pressure combustion furnaces with a common discharge conduit for the products of combustion, one furnace heating a vapor generator, the other furnace heating a vapor superheater receiving vapor from the vapor generator, and each furnace having an independent fluent fuel and fluid oxidant supply, including; controlling the fuel and oxidant supply to the superheater furnace to satisfy steam demand upon the process; controlling the fuel and oxidant supply to the vapor generator furnace to maintain optimum final steam temperature; discharging products of combustion to the submarine exterior; maintaining the furnace pressure relatively constant at various levels of submergence; and limiting both fuel and oxidant supplies from the interior pressure of the submarine.

2. The method of claim 1 including withdrawing air from the submarine interior at a relatively constant rate as combustion oxidant and returning excess air continually to the interior of the submarine.

3. Apparatus for control of a steam generating plant of a submarine propulsion unit having two pressure combustion furnaces with a common discharge of products of combustion, one furnace heating a vapor generator, the other furnace heating a vapor superheater receiving vapor from the vapor generator, and each furnace having an independent fluent fuel and fluid oxidant conduit from a common supply, including; a master steam pressure controller regulating the fuel and oxidant supply means for the superheater furnace in parallel; a master steam temperature controller regulating the fuel and oxidant supply means for the vapor generating furnace in parallel; and flow ratio determining-controlling means for fuel and oxidant of each furnace separately readjusting the fuel supply means for each furnace.

4. The combination of claim 3 wherein the common oxidant supply for the furnaces includes, a compressor for the oxidant, a single conduit for the oxidant output of the compressor, a separate conduit from the single conduit to each of the furnaces, a meter in each oxidant conduit manifesting the rate of oxidant supply to each furnace, and a compressor spill-over valve in the single conduit simultaneously positioned by the master steam pressure controller and both oxidant meters.

5. The combination of claim 3 wherein the oxidant supply system for both furnaces includes, a main compressor driven by a steam turbine utilizing a portion of the generated steam, and a gas expander, duct means conveying products of combustion from both furnaces to the expander, a steam throttle valve for the steam turbine, a single duct for the compressor output, a separate duct for each of the furnaces from the single compressor duct, meters in each of the separate ducts, and a throttle valve for the steam to the turbine under the conjoint control of the master steam pressure controller and the oxidant meters.

6. The combination of claim 3 wherein a compressor draws air from the submarine interior for both furnaces, and a pressure responsive means is arranged to decrease the rate of fuel and oxidant supply when the interior pressure of the submarine decreases below a predetermined value.

7. The combination of claim 6 including a valve in each of the fuel lines to the furnaces, and a single pressure responsive device arranged to trip the valves closed simultaneously upon the interior pressure of the submarine going below a predetermined value.

8. The combination of claim 3 wherein, the separate oxidant supply conduits for each furnace are connected to a common supply of pressurized oxygen, a separate oxygen control valve is located in each of the supply conduits, a separate oxygen flow rate meter is located in each of the supply conduits, a control system for the oxygen valve of the superheater furnace to position it conjointly from the master steam pressure controller and the superheater oxygen flow rate meter, a control system for the oxygen valve of the vapor generating furnace to position it conjointly from the master steam temperature controller and generator oxygen flow rate meter, and a control system for regulating the amount of products of combustion recycled through each furnace to dilute the oxygen going into each furnace.

9. The combination of claim 8 in which the control system for the products of combustion includes, a common duct from the furnaces, separate ducts from the common duct back into the burners of each furnace, a gas flow rate meter in each of the separate ducts, a valve in each separate duct, and a control system for each valve to position each valve in conjoint response to the oxygen flow into meter of that furnace and the gas flow rate meter of that furnace.

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