Development and Experience with a Supercharged Steam Generating System

W. A. FRITZ, Jr., A.B.* and T. P. TURSI, Jr., B.Sc.†

This paper describes the supercharged steam generating cycle as currently employed in the U.S. Navy. In this cycle gas pressure in the boiler varies with load to a design peak of five atmospheres. The boiler receives its air for combustion from an air compressor which is powered by boiler exhaust gases expanding through a gas turbine. An historical background of the cycle and its components follows. Since a number of systems of the supercharged type has been and is being subjected to test at the Naval Ship Engineering Center, Philadelphia Division, the components of the systems, with particular emphasis on the boilers, are described. Advantages and disadvantages of the system are detailed and evaluated. The conclusion is that advantages are significant and that suspected problems or disadvantages do not need to exist if it is understood that the supercharged steam generator is regarded not as just another boiler, but rather as a precision piece of equipment. The test programme at the Philadelphia Division of the Naval Ship Engineering Center is defined as to scope and objectives. Test results are discussed and modifications required as a result of tests are described. Finally, there is a short review of shipboard operating experience to the present time. A major point developed is that the introduction of a new type boiler to the Navy's fleet required an R.D.T. and E. effort, a full-scale test programme, a new appreciation of the art of boiler design and manufacture, and a realistic and well-defined training programme, plus the development of new ancillary equipment. The most important of the other equipment is, of course, a compact and reliable supercharger set (air compressor and gas turbine) to provide air for combustion. The successful design of a compact supercharger set is the key to the use of the supercharged steam cycle.

INTRODUCTION

As used in the United States Navy, a supercharged steam generating system consists of:

a) a pressure fired boiler with superheater;

b) a supercharger, which is a gas turbine driven air compressor;

c) a control system for both combustion and feed water regulation.

This paper is primarily concerned with the pressure fired or supercharged boiler. However, because the system is matched and close-coupled, reference will be made to the supercharger and control components.

The term "supercharged", as referred to in this system, relates to a combustion process in the boiler, wherein the pressure of the gases in the furnace is of such a magnitude that useful work may be accomplished by these gases after leaving the boiler. In the particular system to be discussed, the gas pressure in the boiler varies directly with load to reach a design peak of five atmospheres at maximum rating. The boiler receives its combustion air from an air compressor which is powered by expanding the combustion gases leaving the boiler through a gas turbine to essentially atmospheric pressure. Combustion air enters the burner and burner wind box preheated to approximately 550°F (288°C) and at pressures up to five atmospheres. The supercharged cycle as incorporated in Navy ships is shown in Fig. 1.

*Naval Ship Engineering Center, Philadelphia Division, formerly the Naval Boiler and Turbine Laboratory, Philadelphia.
†Naval Ship Engineering Center, Philadelphia Division, formerly the Naval Boiler and Turbine Laboratory, Philadelphia.

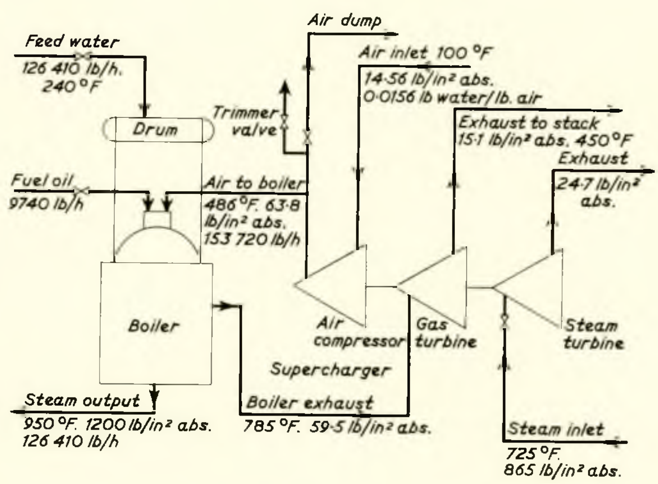

FIG. 1—*Supercharged boiler cycle*

BACKGROUND OF SUPERCHARGED SYSTEMS

The arrangement of the supercharged cycle is similar to that using the well known Velox type boilers introduced by Brown, Boveri in Switzerland in the early 1930s. The French used supercharged boilers, known as Sural boilers, in battleships of the *Richelieu* Class. European experience with supercharged steam generators often employed forced circulation boilers rather than natural circulation. Again, the configurations of the boilers were generally different from those at present in

TABLE I—COMPARISON OF CONVENTIONAL BOILER WITH SUPERCHARGED STEAM GENERATOR

	Conventional boiler			Supercharged steam generator		
	Absorption Btu/h-ft²	Mass flow lb/h-ft²	Total draught loss, per cent	Absorption Btu/h-ft²	Mass flow lb/h-ft²	Total draught loss, per cent
Casing*	—	10 000	7	—	70 000	25
Burner†	—	—	74	—	—	45
Furnace	155 000	2000	—	260 000	8500	—
Screen	50 000	5000	2	120 000	28 000	8
Superheater	47 000	6500	5	90 000	26 000	2
Main bank	20 000	6000	12	35 000	48 500	20

*The increase in casing draught loss in a supercharged steam generator is primarily due to the air inlet and gas discharge connexions. These ducts have mass flows, far exceeding the conventional air encased unit. They consist of only a few feet of 20-in o.d. pipe. The increase in draught loss is compensated for by the reduction in size and weight of the casing over conventional units.

†The reduction in per cent draught loss through the burners, while still maintaining optimum combustion is primarily due to the lower specific volume of the combustion air. However, practically speaking the absolute magnitude of the burner pressure drop (2 lb/in² at full power) assures intimate mixing and minimum excess air requirements.

use by the United States Navy. Boiler weight and space considerations were also not always as assiduously pursued.

In the United States Navy, pressure fired boilers were at one time being considered as part of a submarine steam propulsion cycle. The boiler was to provide steam to the main engines under any condition of operation, surface, snorkel, or submerged. Pressure firing took place with air and oil for surface operation and with oxygen and oil under submerged conditions. Oxygen was to be stored as liquid oxygen, or would be obtained from the chemical decomposition of hydrogen peroxide. Combustion pressure, when surfaced, varied from 20 lb/in² abs to 84 lb/in² abs and, submerged, was to be a constant 600 lb/in² abs. Use of the submarine fossil fired steam cycle was made obsolete by the nuclear steam cycle. However, evaluation of the information received from this cycle led to the design of a surface ship pressure fired boiler and supercharger unit by Foster Wheeler, and Elliott for test and development at the Naval Boiler and Turbine Laboratory under the authorization of the Bureau of Ships. The research and development unit was designed for a destroyer size ship and was subjected to extensive test, development and evaluation programmes beginning in late 1956.

The supercharged steam generating systems which are the basis of discussion for this paper are a direct outgrowth of the research and development programme. The systems have been subjected to extensive tests at the Naval Boiler and Turbine Laboratory. Evaluation of a shipboard type system is continuing for endurance and reliability determinations and for training purposes. Currently, a cycle consisting of a Foster Wheeler boiler, an Elliott supercharger, and a General Regulator control system has been, or is being, installed on seventeen destroyer escort type ships. This system is one of those originally under evaluation. A Babcock and Wilcox boiler, and Ingersoll-Rand and General Electric superchargers, and a Bailey Meter control system are also under test evaluation. It is expected that the exploratory and test work which has been and is being accomplished at the Naval Boiler and Turbine Laboratory will generate the required information for design of a second generation of supercharged steam generating system components. A total of 25 000 hours steaming has been logged on laboratory and ships' units to date.

The Foster Wheeler Pressure Fired Boiler

General Description

The boiler is a natural circulation unit designed to furnish 126 000 lb/h of steam at a final pressure and temperature of 1200 lb/in² gauge and 950°F (510°C). The overall height of the unit is 22 ft and the greatest diameter, 11·5 ft. Weight is 42 tons and box volume 3075 ft³; both figures include supercharger. The heat release rate is 1 400 000 Btu/h-ft³ of furnace volume compared to 500 000 for a conventional Navy boiler. Certain comparative information for the Foster Wheeler pressure fired boiler and a conventional warship type boiler of similar steam output is given in Table I.

As shown in Figs. 2 and 3, the heat exchanger and furnace sections are arranged within a vertical cylindrical pressure casing having a top mounted downfired burner arrangement. The furnace is formed by a cylindrical water wall consisting

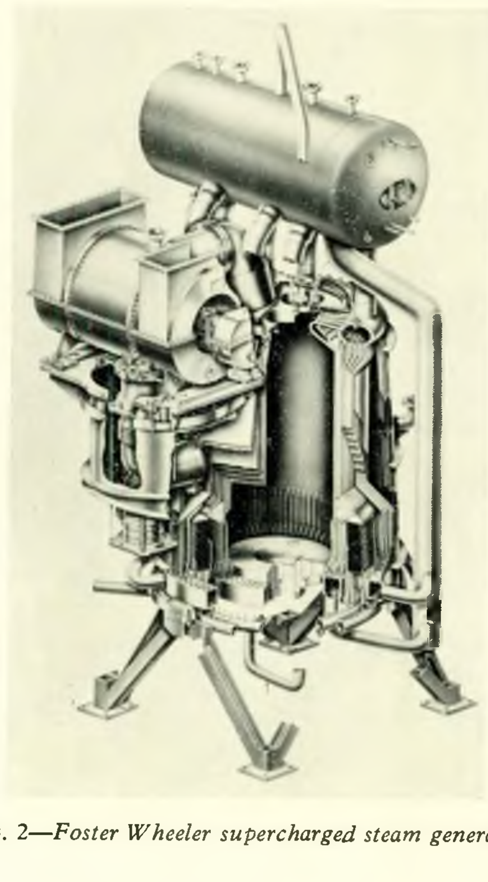

FIG. 2—*Foster Wheeler supercharged steam generator*

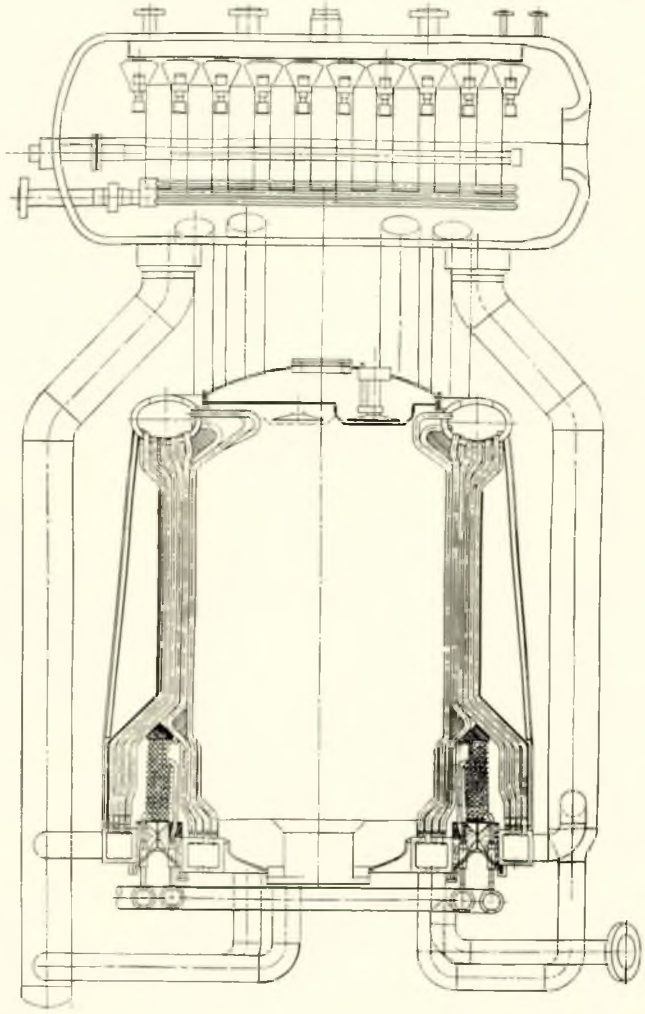

FIG. 3—*Foster Wheeler supercharged boiler—Sectional view*

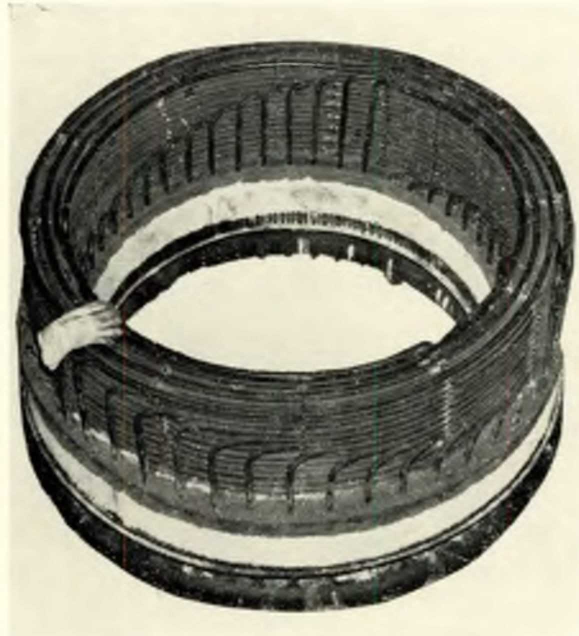

FIG. 4—*Superheater for Foster Wheeler boiler*

of 1½-in o.d. tubes seal welded to adjacent tubes. Access is through a refractory plug located in the furnace floor. The annular space between the furnace cylinder and the pressure casing contains the superheater and the main generating or convection bank surface. A horizontal steam drum, containing steam separating and drying elements, a submerged conduction type desuperheater, and feed water and surface blow piping, is mounted above and external to the main boiler shell. External downcomers and risers provide the necessary connexions to the steam generating surface. Toroidal in appearance (see Fig. 4) the superheater consists of individual tube circuits each bent to form a flat helix. Helical elements form a single layer of tubes with individual layers then stacked one upon the other. The complete bundle weighs 3500 lb and is inserted into the bottom of the heat exchanger shell to be removable as a unit.

Air/Gas and Water/Steam Circuits

Hot, pressurized air from the supercharger compressor enters the domed head wind box and is mixed with distillate fuel oil in three burners which fire downward into the furnace where combustion occurs. The gases flow downward through the furnace then radially outward through the furnace superheater screen, across the superheater and into the convection sections. Here the gases turn and flow upward and parallel with the convection tube bank, then turn again and flow radially outward into an annular space formed by the convection bank baffle and the casing liner baffle. Gases enter a 20-in pipe, expand through the gas turbine which provides the compressor power and then discharge to the stack.

Feed water is introduced directly to the steam drum at a temperature of 240°F (116°C) where it mixes with the circulating boiler water and flows downward through two 12-in downcomers. Six-inch feeder pipes branch from the downcomers and supply the lower furnace and convection tube toroidal type headers. The saturated water passes through the 1½-in furnace and 1¼-in convection tubes where steam is generated. The resulting steam/water mixture is discharged into a single upper collecting header and is fed through eight eight-inch risers to the steam drum. Conventional type steam separating equipment, including horizontal centrifugal separators, then discharges the dry saturated steam to the superheater inlet header, through the helical superheater elements and to the outlet header and main steam line. Part of the superheated steam is passed through the desuperheater in the steam drum for auxiliary purposes.

Babcock and Wilcox Pressure Fired Boiler

The Babcock and Wilcox boiler is a natural circulation type with the heat absorbing and combustion chamber sections enclosed within double cased vertical cylinder shells (see Fig. 5). The combustion chamber is located in the centre of this boiler and is surrounded by a completely water cooled circular wall. This wall in turn is surrounded by steam generating and steam superheating surface. The outermost circular row of generating tubes is arranged to form a wall around the boiler to provide cooling of the inner casing.

The steam drum is basically vertical in orientation and permits freedom of boiler orientation within a ship. The tube sheet is a hemispherical head and the wrapper sheet is a semi-elliptical head. Between the two heads, a cylindrical section is used. Access to the steam drum is through a man hole at the top of the drum.

Instead of a regular water drum, a torus header is used. Access to the inside of the torus is through hand holes.

Circulation of water within the unit is insured by six downcomers which connect the steam drum to the torus header. In addition, there is a connexion between the torus header and two-inch tubes protecting the inner casing in the area of the superheater.

The entire boiler is double cased. Hot air from the supercharger compressor discharge is delivered to the boiler inlet connexion, which is near the end of the bank. Because of flexibility in design, the air inlet connexion can be moved

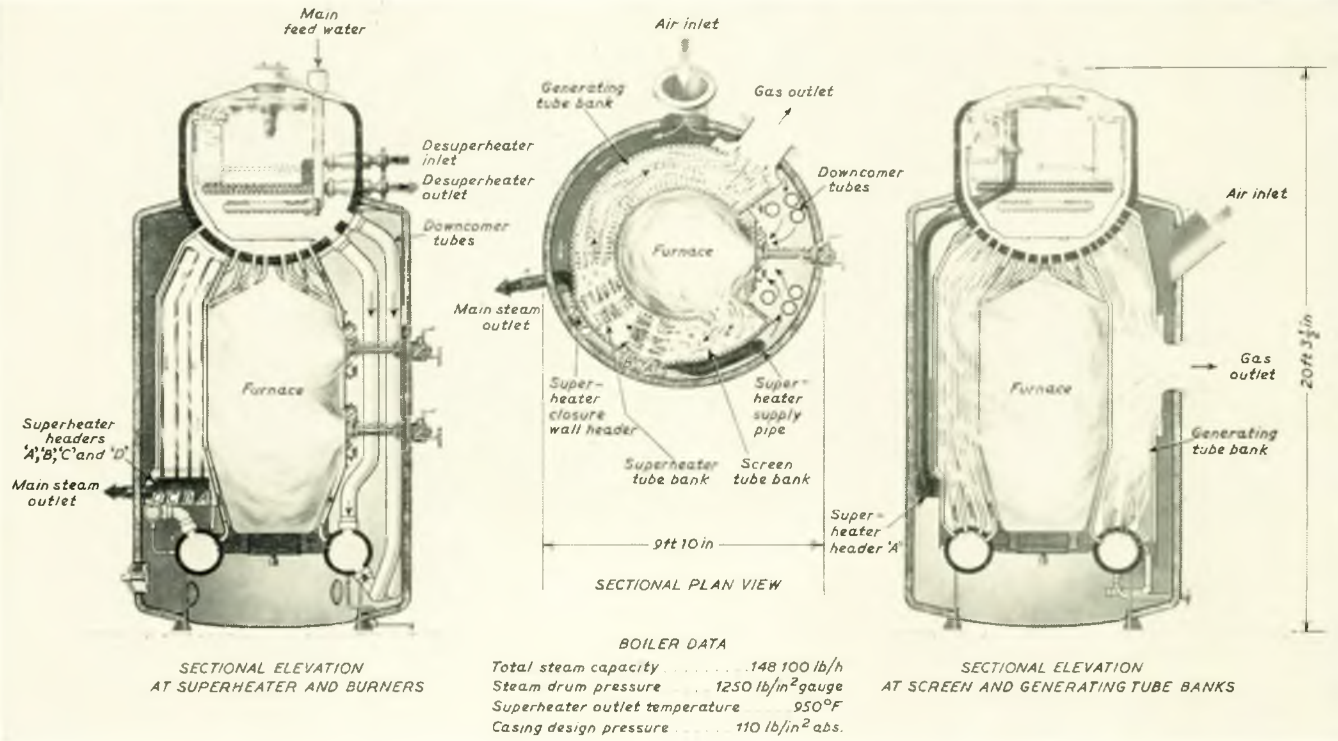

FIG. 5—*Babcock and Wilcox supercharged cylindrical marine boiler*

vertically and horizontally around the outside of the boiler. This permits flexibility of orientation of the boiler with respect to the supercharger. Part of the air flows beneath the boiler, cooling the furnace, and into the wind box. The remainder of the air continues to pass between the inner and outer casing to the wind box. Then, at the two burners, the air is mixed with the fuel and passes into the furnace.

The furnace is essentially cylindrical in shape and, in the cylindrical section, the gas tight feature is maintained by having two inch o.d. tubes welded to bars between the tubes. Above the cylindrical section, the gastight feature is maintained by welding seal bars between the furnace tubes. The bars are protected from burning out by refractory which is held in place by studs.

The screen is arranged so that the gas leaving the furnace makes a 90° turn before entering the superheater. Thus, the screen protects the superheater from direct radiation from the furnace.

The superheater is of the vertical loop type with the headers located at the bottom. There are two steam passes arranged in parallel flow. The steam inlet to the superheater is at the screen end and the outlet is located at the bank end.

The design is such that the superheater can be replaced, if necessary, either in entirety or either one of the two passes and these assembled passes can be brought into the fire-room through standard compartment hatches. The tubes in each of the two passes are arranged in six rows staggered in the direction of gas flow.

The saturated pipe connects the steam drum to the superheater inlet. The saturated steam line, which is directly connected to the dry pipe inside the steam drum, remains within the steam drum, piercing the bottom of the drum, and continues between the boiler inner and outer casing shell to the superheater inlet header. The steam flow nozzle is located between flanged sections in the saturated steam piping within the steam drum. By inserting a blank flange in this section, the superheater is isolated from the boiler permitting chemical cleaning of the boiler water sides.

After passing between the superheater tubes, the products of combustion cross the generating bank where the gas temperature is reduced to that required at the gas turbine inlet. Expansion of the products of combustion through the gas turbine into the uptake provides power to drive the air compressor.

Access to the double cased area is through man holes provided in the boiler outer casing. Access to the boiler furnace for inspection and maintenance is through the lower burner opening. To accomplish this, the lower atomizer assembly must be removed. After the bladed cone is unbolted from the inner casing, there is sufficient room to provide access to the furnace.

Inspection of superheater hand holes and inspection of header water sides and tube seats can also be accomplished from the double casing. In addition, access to the hand holes, water sides and tube seats in the torus header and the superheater side wall header is also accomplished from the double casing.

Superchargers

A marine boiler supercharger, unlike the aircraft gas turbine, is designed with emphasis on long life and accessibility for maintenance. The boiler supercharger must also operate safely and efficiently over a wide range. Therefore, critical speeds in the operating range must be avoided. Additionally, a small lightweight unit is required.

All the superchargers tested at the Naval Boiler and Turbine Laboratory are of single unit design. They are single shaft, gas turbine driven, axial flow air compressors with attached steam turbines for augmenting power and electric motors for initial start-up. Steam turbine augmenting power is used when the gas turbine is not self-sustaining and when booster power is required during periods of rapid acceleration.

The Elliott supercharger is used in the shipboard installations and is coupled to, and supported by, the boiler pressure shell. It has a two-stage reaction gas turbine and an eleven-stage compressor. The complete assembly is 4½ ft in diameter by 11 ft long with a total weight of 11 000 lb. Maximum flow capacity is 180 000 lb/h with a pressure ratio of 5:1 and a discharge air temperature of 550°F (288°C).

Fuel Oil Burners

The burners used in both Foster Wheeler and Babcock and Wilcox boilers are Todd fixed vane diffuser, multi-orifice type and have a turn-down ratio of 25 : 1. Atomization is purely mechanical. Because there is simultaneous operation of all burners at all rates, no adjustable air register doors are required.

Burner wide range performance is achieved by the use of the triple stage atomizer which is essentially a sprayer plate within a sprayer plate within a sprayer plate, as shown in Figs. 6 and 7. Each atomizer barrel consists of three concentric channels, each one feeding a separate stage of the atomizer.

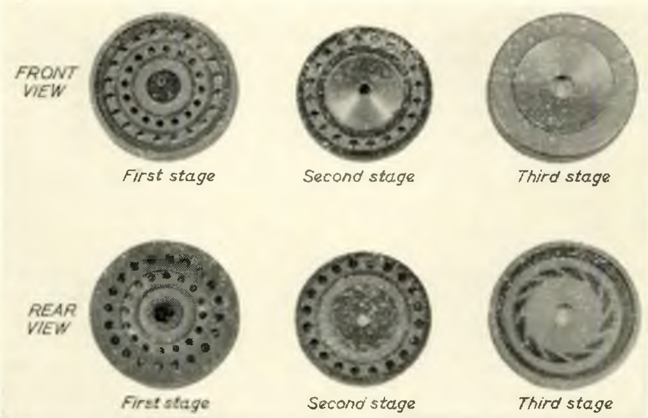

FIG. 6—*Todd triple orifice sprayer plate*

The first stage is sized for light-off flow at full pressure differential, approximately 500 lb/in^2 gauge. When the required fuel flow increases beyond that needed at light-off, oil flow is established in the second stage. When oil flow demand is increased above that provided by the first two stages at full maximum differential, third stage oil flow is established and continues to full differential as required.

Because all burners in each boiler are always in operation and because distillate fuel is used, there is only an emergency requirement for withdrawing a burner during boiler operation, e.g. a plugged atomizer orifice. However, if it should become necessary to withdraw a burner barrel, a purge system and air-lock doors are provided for removal from the pressurized furnace.

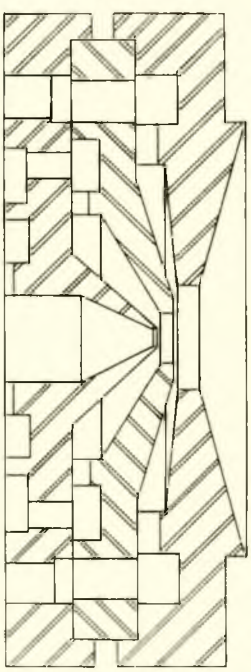

FIG. 7—*Todd triple orifice sprayer plate—Sectional view*

Ignition System

Burner ignition was originally accomplished by a high voltage spark plug installed on the face of each diffuser to ignite the fuel oil. However, the spark plug was susceptible to fouling if not frequently cleaned, which entailed opening the wind box. To insure a more reliable means of ignition, the laboratory designed and built the igniter shown in Fig. 8. The igniter is designed for installation external to the wind box to provide easy maintenance.

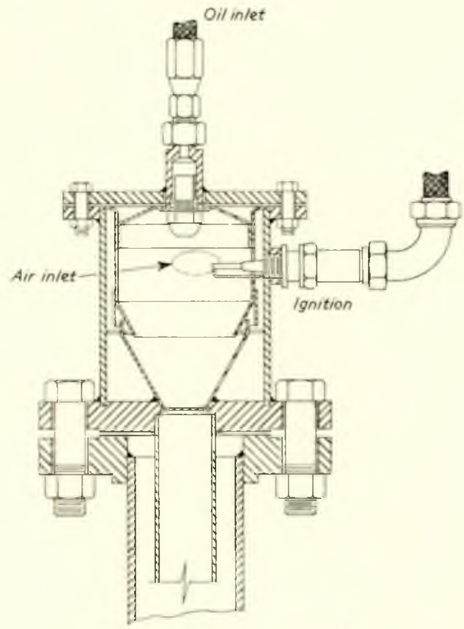

FIG. 8—*Igniter assembly*

This ignition system is interlocked with Fireye flame detection equipment to prevent fuel oil flow to the main burners until flame is established in the pilot burner. As soon as the main burners are ignited the flame detector monitors burner combustion.

Control Systems

The control systems, consisting of a three-element feed water regulator and automatic combustion control, are of the pneumatic type. Ships' systems are by General Regulator, while the Babcock and Wilcox test boiler employs Bailey Meter components. The three elements of the feed water regulator are steam flow, water flow and water level.

The automatic combustion control system functions to maintain steam drum pressure by varying fuel rate and proportioning the flow of fuel and air to maintain optimum combustion conditions. In the operating region below the self-sustaining point (that point where gas turbine power equals required compressor power) combustion air flow is controlled by regulation of the auxiliary steam turbine. Above the self-sustaining point, the gas turbine develops power which provides excessive air for combustion requirements.

This excess air is bypassed around the boiler through an air dump valve regulated by the control system. The essential difference between this control system and those for a conventional boiler exists in the air control loop, since the air dump and auxiliary turbine steam control valves must be sequentially operated to cover the non-self-sustaining and self-sustaining ranges. Under increasing load conditions, the master signal developed from the drum pressure increases air flow which is metered and employed to limit fuel flow to available combustion air. On decreasing load conditions, the master signal is employed to decrease fuel flow immediately, prior to a reduction in combustion air flow. This prevents a fuel rich mixture and smoking at the stack.

Advantages of a Supercharged Cycle

As discussed earlier, the concept of a supercharged steam generating cycle is not new. The primary consideration leading to its adoption by the United States Navy at this time was a reduction in space, but there is a total number of advantages.

Reduction in Space and Weight

This factor is of prime consideration in the design of equipment for warships and, in this system, is achieved from the increased gas densities in the furnace. Combustion rates are, therefore, increased enormously, as are gas side heat transfer coefficients. Convection heat transfer is mainly a function of mass flow and, therefore, with the high gas densities, it is possible to achieve high heat transfer rates by using high rates of mass flow with only moderate draught loss. Heat transfer rate in the convection passes is in the order of 35 000 Btu/h-ft^2. Radiant heat transfer is increased due to the higher emissivity of the combustion gases under pressure and to a high heat release rate which increases flame temperature.

Gains in heat transfer rate make possible a reduction in heating surface to about one-third that of a similar capacity warship type boiler. Because of tube metal temperature and spacing limitations, actual box volume and total dry weight of the boiler and supercharger is approximately one-half that of a conventional boiler with its forced draught blowers. Comparative space and weight figures are as follows:

	Conventional Boiler	*Pressure Fired Boiler*
Box volume of boiler, excluding forced draught blowers or supercharger, ft^3	6340	1890
Box volume of boiler, including forced draught blowers or supercharger, ft^3	7900	3075
Total dry weight of boiler and forced draught blower or supercharger, tons	84	42

Economy of Operation

The gain in economy is achieved by elimination of the steam energy to drive the forced draught blowers and instead deriving the power for driving the compressor from the combustion gases leaving the boiler. Additionally, the supercharger set acts as an air preheater.

Reduction in Maintenance

This reduction is of particular significance to the Navy because of its many remote bases of operation and its rotation of personnel. Lower maintenance factors should also lead to less frequent and shorter boiler downtimes. Reduction in maintenance is the result of many factors:

1) fewer boiler tubes reduce the probability of extensive tube seat leakage;
2) a great reduction in the amount of refractory material required practically eliminates this high maintenance factor;
3) design of the superheater so as to be removed from the boiler as a unit greatly simplifies superheater tube renewal;
4) a combination of factors: high gas pressures and velocities, use of distillate fuels, and symmetrical arrangement of heating surfaces, makes cleaning of fire sides unnecessary and precludes the requirement of soot blowing equipment;
5) a pressure vessel type casing precludes the possibility of casing leakage with attendant repair requirements.

It must be emphasized, however, that reduction in maintenance and increase in reliability can be achieved only if these steam generators are to be subjected to absolutely correct operational and operational maintenance conditions.

Improved Erection Methods

It is possible for the boiler to be erected by the manufacturer and shipped to the erecting shipyard as a complete unit ready for ship installation. This should assure uniformity between units and make "assembly line" type of erection possible. In the event of a major casualty, unit replacement in a ship can be relatively easily accomplished.

Better Manœuvrability and Control

The system is well adapted to automatic control concepts and performs best in the automatic mode. Boiler start-up time is reduced and time of response to load changes is decreased.

Use of More Than One Fuel

Although conventional naval boilers can burn both residual and distillate type fuels, other advanced type cycles are often restricted to one fuel. The pressure fired boiler is intended to be fired using distillate fuel, but has been operated for 80 continuous hours using Navy Special fuel oil at firing rates to 75 per cent of full power. Lighting-off was accomplished without difficulty using the triple-orifice sprayer plates normally used with distillate fuel.

Inspection of the furnace following operation with Navy Special revealed a slight oil impingement on the screen tubes in spots about two feet below the burners. These were small and not considered serious. A thin deposit had formed on the superheater tubes and on the screen tubes at the furnace exit. The gas turbine was found to be clean and free of deposits.

Problems Related to the Supercharged Cycle

As is the case in novel and newly introduced machinery, certain problems arise which, if not recognized, can defeat the successful use of the unit. It has been the determined effort of those connected with the pressure fired boiler to ferret out the problem areas, considered in the following paragraphs, before they occur by engineering studies and tests and by reliability and maintainability studies.

The foremost was the fact that certain operational problems would exist. These were caused by the facts that the system was new, that the intention was to operate it automatically and that it had a supercharger set to replace the forced draught blowers. The operational problems plus stringent maintenance and repair procedures have been solved by intensive training programmes at the Naval Boiler and Turbine Laboratory and at the Naval School–Boilermen, Philadelphia.

Because of problems created by boiler compactness, welded construction and limited access, maintenance advantages already discussed could be nullified. Training has so far obviated this problem area. As LiCausi[1] stated, after discussing rigid erection requirements:

> "The immediate reaction to these fabrication requirements may well be negative if the supercharged steam generator is considered a boiler. Many readers in the marine industry have designed, fabricated, operated, and serviced units running the gamut from Scotch and sectional-header boilers to the latest D-type units operating at 1200 psig and 950°F. You have witnessed the transition from riveted joints to class one weldments requiring X-ray inspection. Boiler repair once required a sledge hammer, a file scraper, and a caulking gun. Today's boiler, unlike the old Model T, cannot be kept running with baling wire and a screw driver.
>
> The supercharged steam generator is designed to be maintained using modern tools and modern methods. Because of the compactness, even heat absorption and careful design, it is expected that the total amount of maintenance required for this type of unit will be less

than that encountered on D-type boilers."

Extreme cleanliness of boiler water sides is a requirement to prevent tube overheating because of the high heat absorption rates. It has been demonstrated that strict adherence to conventional Navy 1200 lb/in^2 gauge boiler feed water treatment procedures is sufficient to maintain water side integrity. This is a split treatment using caustic soda and disodium phosphate to maintain *p*H at 10·4 to 11·0 and phosphate at 10 to 25 ppm. Surface blow-downs are required daily and bottom blows every 48 hours or as close thereto as possible. Chlorides are not to exceed two epm. De-aerated feed water is used and the boiler is steam or nitrogen blanketed when idle.

Primarily because of the gas turbine and secondarily in the interest of maintaining clean fire sides, a distillate fuel was to be burned. Wide range fuel oil burner and service pump problems were envisaged. Both reliable burners and pumps were developed early in the test programme. Burning of distillate fuel was a distinct advantage in maintaining clean boiler fire sides. As discussed earlier, it was shown that a residual fuel could be used in emergencies.

Compact size, close tolerances and integral unit construction could provide serious problems in operation and performance. This stems from the fact that, once the boiler has been erected, any flaws in its construction become exceedingly difficult to correct. "Boilermaker's feel" cannot be tolerated in erecting a pressure fired boiler. For example, any small gas baffle leaks may be the cause of a casing "hot spot" or of upsetting gas side temperature and pressure equilibrium. It, therefore, becomes mandatory that an excellent system of quality control be exercised during boiler erection.

High furnace pressures mitigate against periodic removal of fuel oil burner atomizers for cleaning. Burning of distillate fuel has made it unnecessary to clean atomizers at an interval of less than one week.

SCOPE AND OBJECTIVES OF TEST PROGRAMME

Equipment Tested

The laboratory has completed or is continuing research and development and performance testing of four supercharged boilers and six superchargers. Dates of testing and operating hours attained are listed in Table II. The Foster Wheeler production boiler and Elliott production supercharger comprise a system which is identical to that being installed aboard the DE-1040/DEG-1/AGDE-1 Classes of ship. The prototype boiler was the first produced under the production contracts and is very similar to the ships' boilers. Subsequent discussions of test result and developmental modifications are based primarily on the performance testing of this boiler. All major modifications were ultimately incorporated into the shipboard boilers.

TABLE II—SUPERCHARGED STEAM GENERATING SYSTEM EQUIPMENT TESTED AT N.B.T.L.

	Dates tested		Total operating hours
	From	To	
Steam Generators:			
FOSTER WHEELER			
Developmental	Nov. 1956	Jun. 1962	1700
Prototype	Jun. 1962	Present	4500
Production	Apr. 1964	Present	2500
BABCOCK-WILCOX			
Developmental	Jan. 1964	Oct. 1965	1250
Superchargers:			
ELLIOTT			
Developmental	Nov. 1956	Feb. 1960	1200
Production No. 1	Jun. 1962	Mar. 1963	730
No. 2	Mar. 1963	Present	3870
INGERSOLL-RAND			
Prototype	Sept. 1963	Feb. 1965	1650
Production	Aug. 1965	Present	750
GENERAL ELECTRIC			
Prototype	Aug. 1960	Feb. 1964	780
Production	Feb. 1964	Oct. 1965	970

Objectives

The suitability of the supercharged steam generator cycle for use in propulsion of naval combatant ships was demonstrated[2] by a test of the Foster Wheeler development boiler in conjunction with the Elliott and General Electric development superchargers. Objectives of the shipboard equipment test programme were as follows:

a) to determine ability of equipment to meet minimum specification requirements as regards steady and transient load performance; of specific concern were:
   1) combustion performance;
   2) steam purity performance;
   3) boiler circulation characteristics;
   4) superheater and desuperheater performance;
   5) supercharger surge characteristics;
   6) supercharger steam assist requirements;
   7) efficiency;
   8) automatic controls performance;
   9) load response;
   10) suitability of operation while raising steam and securing;

b) to determine suitability of the equipment during emergency and casualty operations, such as:
   i) emergency high speed lighting-off;
   ii) supercharger surge;
   iii) boiler tube failure;
   iv) burner mal-function;
   v) interruption of electrical power;
   vi) loss of control system air supply;
   vii) local-manual control;
   viii) supercharger overspeed;
   ix) contaminated fuel;
   x) contaminated feed water;

c) to evaluate the suitability of appurtenances and safety devices;

d) to develop and evaluate design modifications to attain required performance characteristics;

e) to evaluate equipment arrangements as concerns access and adaptability for inspection, maintenance and repair;

f) to develop and evaluate detailed operational, maintenance and repair procedures;

g) to evaluate the ability of the equipment to perform in a satisfactory manner over an extended period of operation;

h) to insure that required modifications to equipment and procedures were adequately identified and factored into the production, installation and operation phases;

j) to guide the installation, start-up, trial, operation, maintenance and repair phases on the ships;

k) to assess and improve reliability and cost effectiveness factors using actual failure rate and repair/maintenance cost data from shipboard operation and laboratory testing.

DEVELOPMENT MODIFICATIONS

Fuel Burners

Initial combustion performance of the burners was characterized by secondary combustion, heavy sooting and excessive gas temperatures within the generating tube bank and gas outlet annulus. These conditions reduced system performance characteristics by causing:

1) excessive baffle, outer casing, and generating tube temperatures;
2) reduced boiler efficiency due to a reduction in heat absorption caused by the insulating effect of soot on the tubes;
3) increased boiler exit gas temperature;

4) a reduction in the maximum allowable supercharger speed due to the lower tolerance of gas turbine blading to centrifugal forces at the higher gas temperature;
5) reduced surge/stall margin of the supercharger air compressor due to the higher gas side pressure drops resulting from high gas temperatures.

These combustion performance deficiencies were caused by burner, wind box and furnace configuration changes incorporated into the production design as a result of vertical space limitations. It was also established that gas flow patterns within the furnace were non-symmetrical and that air flow to the burner registers was not equal. The problem was corrected by air register configuration changes.

These changes resulted in excellent combustion performance at all steaming rates; smoke control was satisfactory and fire side sooting was practically non-existent. Normal operation was conducted with five to seven per cent excess air. It was noted, however, that when the burners were operated with less than two per cent excess air, sooting occurred.

Burners were required to be safely removable while the boiler was being fired to allow for replacement of a malfunctioning unit. This required mechanical arrangements to prevent blow-back of hot gas from the furnace. The design selected for this requirement was a flapper valve which closed under spring tension when the burner was partly removed. An interlock prevented full removal of the burner until the flapper valve was fully closed. Problem areas were:

i) binding of the flapper valve shafting;
ii) binding of the burner barrel in its housing;
iii) failure of interlock to perform as required;
iv) distortion of burner receiver components.

Significant improvements have been made in the elimination of these problems.

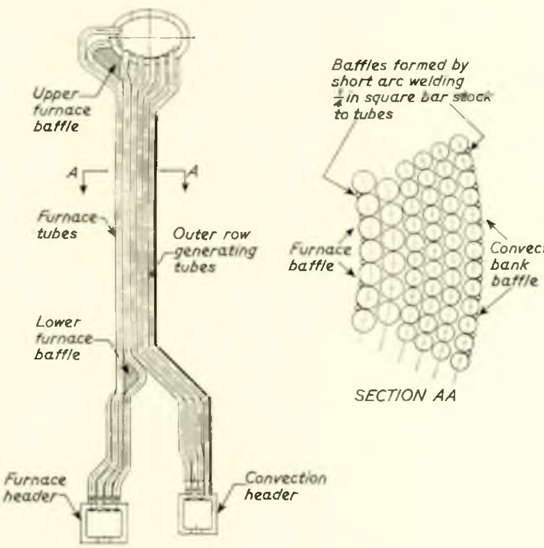

FIG. 9—*Foster Wheeler boiler generating bank*

Furnace Tubes

First row furnace tubes were assembled in a cylindrical arrangement and were tangentially welded to one another to form the furnace wall as shown in Fig. 9. Three of these tubes failed while the test boiler was operating at the overload steaming rate. The failures were semi-thick lipped ruptures located on the furnace face of the tubes approximately 80 per cent of the tube length from the bottom. Examination of the tubes confirmed that the failures resulted from localized overheating. Preliminary investigations confirmed that the overheating was not a result of water side deposits or low water.

New tubes were installed with thermocouples to indicate metal temperature in various locations including the failure points; several other tubes throughout the furnace were similarly instrumented. The following investigations were conducted to determine the nature and cause of the tube overheat.

The boiler was operated with average boiler water conditions (300 ppm total dissolved solids concentration) at all rates through overload. Tube metal temperatures did not exceed 750°F (399°C) in any location. Total dissolved solids concentration was then increased to the maximum allowable of 1150 ppm. At the 95 per cent full power rate, tube metal temperatures (in the area of the previous failure) rapidly increased in excess of 1200°F (649°C); the firing rate was quickly reduced and temperatures returned to normal. Results of this test were confirmed on several re-runs.

A swirler or turbulator was installed in the affected tubes several inches below the lowest point of overheat. The boiler was operated to the overload rate with contaminated boiler water; no tube overheat occurred.

Based on these and related investigations, the following conclusions were reached:

a) tube overheat was localized in the upper portions of certain tubes adjacent to one burner;
b) the cause of overheat was film boiling which allowed the moisture film to be separated from the tube wall by a layer of steam vapour which had a low thermal conductivity;
c) film boiling was probably produced by a concentrated heat input to the tubes from the adjacent burner in a region of relatively high steam volume;
d) water chemistry influenced the overheat.

Generally, it was concluded that the solution to the problem lay in an increase in furnace tube circulation and flow characteristics or in elimination of the concentrated heat input. Since modification to correct water side conditions would have been difficult to attain without extensive boiler redesign, burner changes were investigated. It was determined that reversing the direction of rotation of the throat ring blades of the adjacent burner produced the desired effect. It was concluded that the flow vectors produced by this burner were reinforced by air flow vectors in the wind box, thus producing the undesirable concentration of gas on one side of the furnace. Reversing the direction of the throat blades in this one burner allowed these vectors to cancel.

Subsequent to this burner modification, the boiler was operated at the overload firing rate continuously for five hours with fully contaminated boiler water. No tubes overheated.

Convection Bank Baffle

The convection bank baffle consisted of a $\frac{1}{4}$-in thick 310 stainless sheet wrapped around the outer row of generating tubes. This baffle was required to turn the superheater exit gas vertically upward and cause it to flow within the convection tube bank. The baffle was subjected to extreme overheat, buckling and cracking.

After 170 steaming hours, the baffle was removed and the

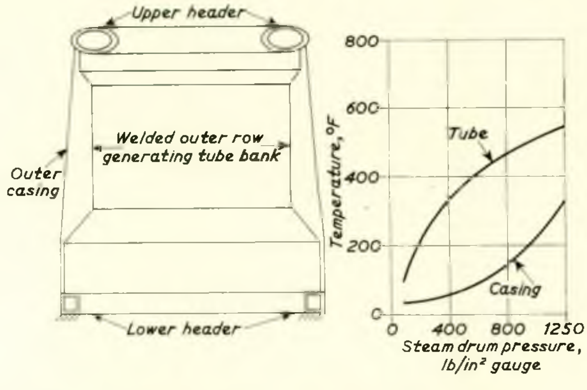

FIG. 10—*Foster Wheeler boiler—Configuration and temperatures of tubes and casing*

outer row of generating tubes was tangentially welded to form a water-cooled baffle, see Fig. 9. The original baffle was replaced with a 405 stainless baffle as a back-up to the welded tubes.

This method of baffling proved very successful because of the efficient fin cooling by the tubes. No baffle deterioration was experienced in 3000 hours of operation in one test boiler. As discussed in the next section, however, the welded configuration produced excessive tube stresses.

Outer Row Convection Tubes

After 2700 hours of operation, several of the welded outer row generating tubes experienced fatigue failures. Welding of these tubes produced the cylinder and cone configuration shown in Fig. 10. These tubes joined the upper and lower headers which were also rigidly joined by the boiler casing, a ½-in thick, cylindrical, steel pressure shell. Investigations showed that during boiler light-off, the outer casing temperature was lower than the tube temperature by 400 deg F (222 deg C); at the full power steaming rate, the casing exceeded the tube temperature by 250 deg F (139 deg C). These temperature differentials produced a load cycle on the tubes which caused a stress concentration at the tube bends.

Analytical investigations indicated stresses in excess of the yield point of the tubes and a relatively short cycle life. Analysis further indicated that, by limiting the temperature differential to ± 75 deg F (± 42 deg C), a fatigue life of 30 000 cycles could be attained, whereas 10 000 cycles was considered adequate for the life of a boiler. In addition, it was determined that a theoretically infinite cycle life could be attained by also reducing the welded fin section.

Two solutions to the problem were, therefore, developed. The first included a casing heating coil designed to reduce the casing temperature lag during light-off. This heating coil was supplied with saturated steam from the boiler and was secured when the boiler was brought to operating pressure. Associated with this was a reduction of casing outer lagging to reduce the casing temperature at higher operating rates. The second involved a reduction in the welded fin cross-section together with the addition of casing heating coils and reduction of outer casing lagging. The first solution was applied to production boilers which were already constructed; the second was applied to subsequent production boilers.

Each of these configurations was installed in one of the test boilers at the laboratory. The welded outer row tubes were instrumented with thermocouples and strain gauges; the outer casing was instrumented to obtain temperature and growth data. Data were taken under various lighting-off, operating, securing and lay-up procedures both with and without the casing heating coil in operation. It was established that the casing to tube differential temperature could be easily maintained within the anticipated ± 75 deg F (± 42 deg C) under all normal operating conditions.

The authors are of the opinion that additional refinements of these solutions are required, but this will no doubt be contingent on results of extended steam operations currently being conducted at the laboratory, shipboard operating experience and further analysis of the strain and temperature data obtained on test.

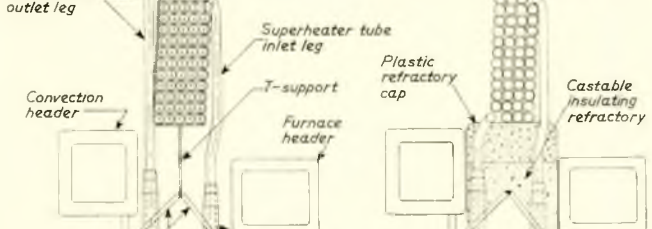

FIG. 11—*Foster Wheeler boiler—Superheater support structure*

Superheater Support Structure

The superheater support structure was originally as shown in Fig. 11(a). The tube spacing was maintained by 0·25-in diameter, 25 per cent Cr, 20 per cent Ni rods installed perpendicular to the tube axes. The whole tube bundle rested on a 25 per cent Cr, 20 per cent Ni T-shaped support plate supported by the superheater seal plates which were attached to the boiler foundation via the generating headers. The inlet and outlet legs of the superheater tubes penetrated, and were welded to, thermal sleeves in the seal plates. These tube legs supported a very large proportion of the weight and vertical loading of the superheater.

Three problems were encountered with this supporting structure:

1) overheating of the seal plates;
2) burn-out of the T-support;
3) burn-out of the tube spacer rods.

The final configuration was as shown in Fig. 11(b). In this configuration, the T-support was eliminated and the entire seal plate void was filled with insulating refractory which was protected from erosion by a plastic refractory cap. The vertical tube legs (96 each of one-inch o.d. by 0·120-in wall) supported the superheater with little bearing load being placed on the refractory. The ¼-in spacer rods were replaced by octagonally shaped 25 per cent Cr, 20 per cent Ni collars shrunk-fit to the tubes to provide for cooling. After 1500 hours of operation, this modified support configuration has experienced no observable deterioration.

Superheater Tubes

The superheater tube elements were fabricated from A.S.T.M. Grade 316H (18 per cent Cr, 8 per cent Ni, 0·04-0·10 per cent C) austenitic stainless steel tubing of one-inch o.d. by 0·120-in wall. In the operating temperature range of 900° to 1200°F (482° to 649°C), this material became sensitized, i.e. the formation of chromium-carbides depleted chrome from the grains adjacent to the boundaries. The material then became susceptible to intergranular stress corrosion attack.

Gas side corrosion occurred as a result of water combining with normal gas side deposits. This corrosion, in conjunction with stress imposed on the tubes by distortion of the superheater T-support, Fig. 11(a), resulted in stress corrosion cracking of the tubes. A limited amount of steam side cracking occurred as a result of the normally low quantity of impurities carried over in the saturated steam.

Laboratory tests demonstrated that low carbon (less than 0·035 per cent) stainless steel was not as susceptible to sensitization or stress corrosion attack as the material used. Future superheater designs will use this or similar materials.

Stress corrosion was mitigated in the current shipboard superheaters by eliminating stress imposed by the T-support plate and by careful control of moisture and corrosives on the tube fire sides and steam sides.

Final Steam Temperature

The superheater tube surface was reduced because of the high final steam temperature. This was accomplished by removing equal lengths of tubing from each circuit. In the initial modification, eight per cent of the surface was removed, but final steam temperature was not affected. It was subsequently determined that the original superheater installation permitted gas to bypass above the superheater and thus caused a reduction in final steam temperature. Installation of the superheater following removal of tube surface eliminated this bypass and thereby compensated for the reduced surface.

After correct superheater installation, it was still necessary to remove an additional 11 per cent of the original surface to attain the required final steam temperature. Performance

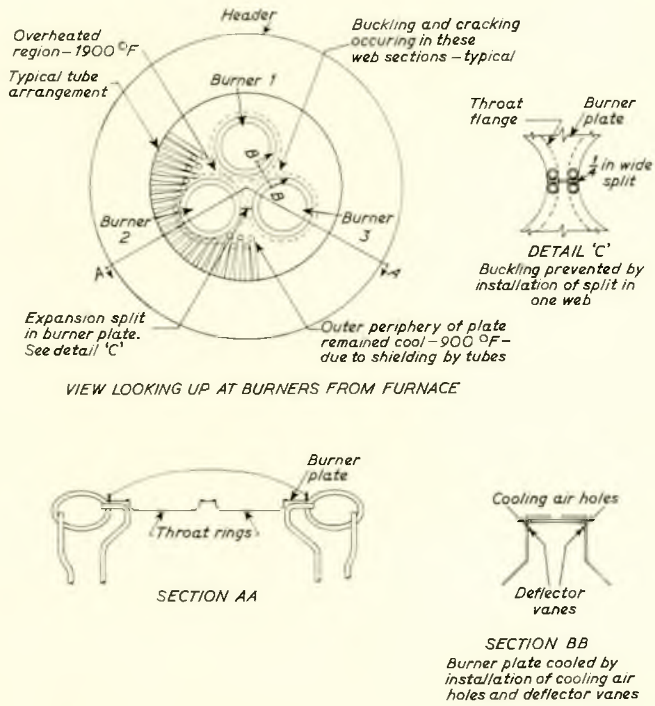

FIG. 12—*Foster Wheeler boiler—Wind-box plate*

results of this final superheater configuration are discussed in a later section.

Wind Box Plate

The boiler wind box was formed by a dome shaped top section ($\frac{3}{8}$-in thick, 54-in diameter) and a flat $\frac{1}{4}$-in thick 25 per cent Cr, 20 per cent Ni bottom plate, Fig. 12. The burner throat rings, attached to the lower plate, and the air diffuser plates were hung from the dome. In order to achieve proper combustion performance, it was necessary that alignment of these burner components be accurately maintained. The lower plate, however, was subject to thermal distortion and cracking which caused misalignment of the throat rings and diffuser plates.

Several burner plate/throat ring configurations were evaluated and various plate temperature data obtained. Distortion of the plate resulted from the temperature differential which existed between the web sections and the periphery of the plate. The webs averaged 1400°F (760°C) with localized temperatures of 1800°F (982°C) while the periphery averaged 900°F (482°C). This temperature difference caused the web sections to buckle and subsequently crack during cooling.

One web of the burner plate was split to allow for thermal expansion of the plate as shown in Fig. 12. No distortion of the plate occurred after 800 hours of operation. Subsequently, bleed air holes were installed in the throat rings to provide a cooling air flow across the overheating sections of the plate as shown in Fig. 12. The burner plate did not exceed 1300°F (704°C) following this modification; 25 per cent Cr, 20 per cent Ni stainless steel has acceptable corrosion resistant properties to 1600°F (871°C).

Compressor Stator Blades

The Elliott supercharger compressor stator blades originally had a single tang (0·093-in square) on each end which were spot welded into mating holes in tip and root shrouds. The root shrouds were held in dovetailed grooves in the rotor casing. During operational testing, a second row stator blade broke loose and carried through the compressor causing extensive damage to other rotor and stator blades. Post failure inspection revealed that most stator blades upstream of the failure had cracked tangs. Improved blade and shroud designs were developed incorporating substantially larger tangs and fillet radii, a slotted and threaded shroud to blade adapter and improved welding techniques. This modified configuration has performed satisfactorily for several thousands of operating hours; post-operational inspection showed no failures.

TEST RESULTS

This section will discuss performance test results of the Foster Wheeler boiler, Elliott supercharger and General Regulator control system after incorporation of the development modifications previously discussed.

Burner Performance

Burner combustion performance, stability and controllability were good. The triple orifice atomizer permitted operation over the entire load range from lighting-off to overload rate without the need of a burner change. This range is equal to a turn-down ratio of 19 for the burners. Distillate fuels (Diesel or high energy aircraft) were used primarily to eliminate gas turbine fouling/corrosion problems, but were also a benefit to burner and boiler cleanliness. The burners were operated on numerous occasions for 200 to 300 hours without cleaning and without any deterioration in combustion performance. On one occasion, a boiler was operated satisfactorily for 800 hours without cleaning burners.

In the operating range, above 15 per cent of rate, the burners commonly operated with excess air quantities of five to seven per cent. Below 15 per cent of rate, excess air quantities to 15 per cent were required to assure burner stability. This, however, was expected since air register openings were not variable. Typical flue gas analyses data are given in Fig. 13.

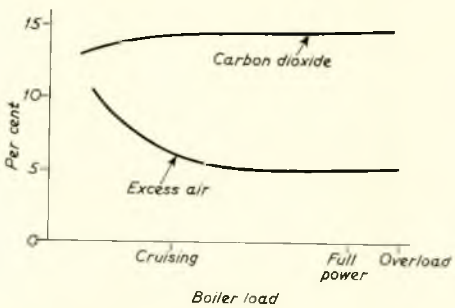

FIG. 13—*Foster Wheeler boiler—Flue gas analysis*

Combustion performance and overall boiler performance were evaluated with one and two burners in operation up to the full capacity of the burners. This was done to assure that operation could continue while one or two burners were being changed due to mal-functioning. One burner permitted operation to 40 per cent of rate and two burners to 80 per cent of rate. During this operation, excess air increased significantly since the air registers were not equipped with shutters; however, burner stability, combustion performance and gas temperature distribution throughout the boiler remained satisfactory.

Due to the small furnace size, mal-functioning or improper operation of the burners tended to result in deposition of soot in the generating bank. If such mal-functioning persisted for a long enough period of time, these deposits tended to cause an increase in boiler exit gas temperature and a consequent reduction in boiler efficiency due to their insulating effect. It was determined, however, to be a simple matter to completely eliminate this soot by operating with increased excess air.

A discrete discontinuity in the fuel pressure/flow relationship due to the triple orifice atomizer characteristics was compensated in the automatic control system by introducing an opposite non-linear function to produce a linear fuel demand/

flow relationship. Trained operators easily became acclimatized to this discontinuity and had little difficulty with manual control.

Superheater Performance

Overall superheater performance was satisfactory. Steam temperature at the superheater outlet with the original superheater was higher than design at all firing rates as shown in Fig. 14. Following removal of 19 per cent of the original

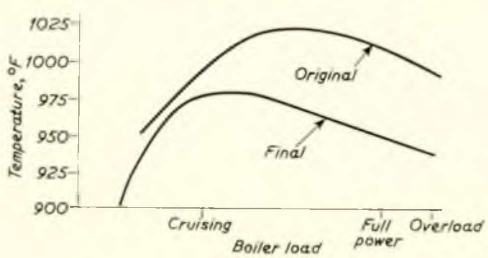

FIG. 14—*Foster Wheeler boiler—Final steam temperatures*

tube surface and tightening of the superheater upper gas seal, temperature was at acceptable values as shown in Fig. 14.

Steam pressure drop from the steam drum to the superheater outlet was 20 lb/in^2 greater than design at the full power rate. Removal of superheater heating surface did not materially change this pressure drop since the total number of tube elements remained constant.

At the maximum firing rate, average superheater heat absorption was 90 000 Btu/h-ft^2 of external tube surface, compared with 45 000 Btu for conventional steam generators. Peak values, however, were very close to the mean due to the uniformity of gas flow throughout the supercharged boiler, whereas in conventional boilers, peak values may be significantly in excess of the mean. This uniformity of heat absorption produced uniform tube temperatures within the gas path. Maximum values were 1150°F (621°C) at the 60 per cent firing rate. Generally, 1200°F (649°C) is considered an acceptable maximum operating temperature for 18 per cent Cr, 8 per cent Ni stainless steel superheater tubes, although, for the particular grade used, sensitization of the material did occur at operating temperatures as previously noted.

Circulation Characteristics

Circulation characteristics were determined by calculating the percentage of steam by volume leaving the risers and also by installing cadmium wires in a number of furnace screen and convection bank tubes. To determine the percentage of steam by volume, downcomer flows and flow to furnace and convection bank headers were measured by means of calibrated Pitot tubes; steam generated in each bank of tubes was calculated from gas path analysis based on measured gas temperatures before and after the superheater and after the convection bank.

At the overload steaming rate, the percentage of steam by volume in both the furnace and convection banks was 76. These values indicated adequate circulation as was also attested by the fact that no cadmium wires were burned out.

Draught Loss

The total draught loss through the boiler was 60 per cent in excess of design. While this improved boiler efficiency, it significantly reduced supercharger efficiency and, consequently, increased the supercharger make up steam requirements. Boiler draught loss could not be reduced without extensive design modifications to the boiler and was, therefore, not reduced. Reduction of boiler draught loss must necessarily be a major consideration in the design of future supercharged steam generators.

Steam Purity

Moisture carry-over in the saturated steam was determined to evaluate the efficacy of the steam separating equipment. Tests were conducted at the overload firing rate with the boiler water contaminated to 1150 ppm total dissolved solids concentration and with steam drum water level at three inches above normal. Results were satisfactory; moisture carry-over was 0·18 per cent; maximum allowable carry-over is 0·25 per cent.

Efficiency Performance

Efficiency of the boiler and supercharger was determined at various rates. A boiler efficiency of 84 per cent and a combined plant efficiency of 82 per cent were obtained at the full power rate. This can be compared to a plant efficiency of 75 per cent for a conventional naval destroyer boiler. Complete efficiency characteristics and an anticipated design value are given in Fig. 15.

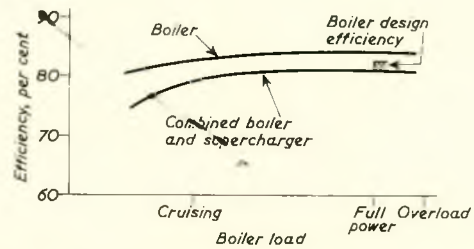

FIG. 15—*Foster Wheeler steam generating system efficiency*

Supercharger

The mechanical performance of the supercharger was satisfactory for all modes of operation. After redesign of the compressor blades and some minor modifications related to the bearings and auxiliary equipment, no mechanical problems were encountered. Structure-borne vibration was within specification limits over the entire load range, reaching a maximum of one mil. There were no critical rotor speeds within the operating range.

Thermodynamic performance of the supercharger was highly dependent on the operating characteristics of the boiler. The boiler draught loss and exit gas temperature exceeded anticipated design values and contributed to a reduction in compressor surge margin and an increase in supercharger assistance power requirements.

Compressor surge occurred in the medium to low rate region as a result of these off design conditions of the boiler, as well as a lower than anticipated compressor surge line [see

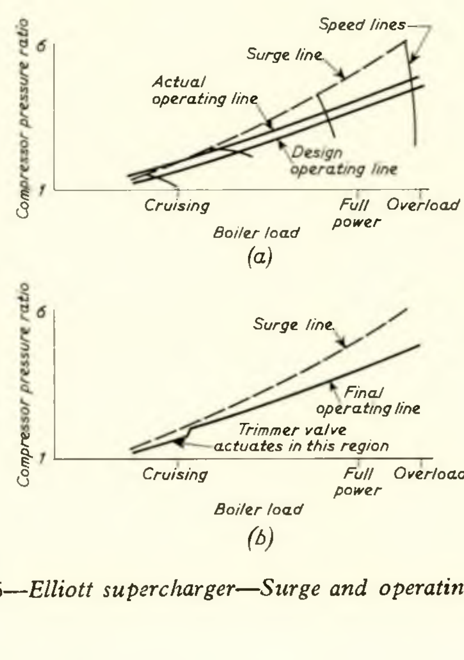

FIG. 16—*Elliott supercharger—Surge and operating lines*

Fig. 16(a)]. Surge was eliminated by use of a trimmer valve which bypassed a portion of the compressed air around the boiler and thus lowered the effective system operating line [see Fig. 16(b)]. This technique caused an unbalance in the compressor and gas turbine power levels and thereby increased steam assistance requirements. The final steam assistance requirements, however, did not significantly reduce overall plant efficiency.

Additionally, compressor inlet air temperature, compressor fouling and large quantities of excess air to the burners were found to increase the steam assistance requirements of the supercharger. Fig. 17 shows the assistance power requirements for various inlet air temperatures.

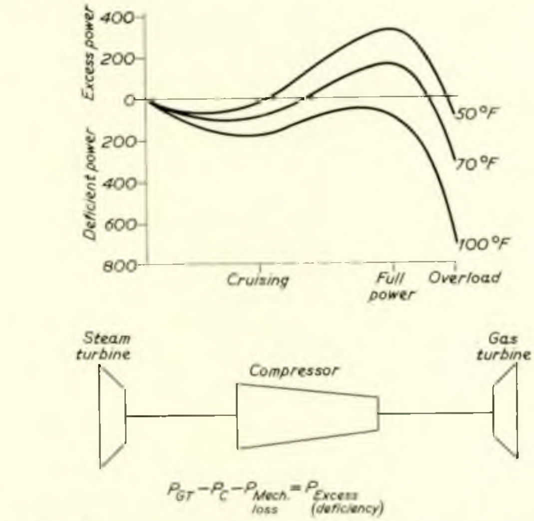

FIG. 17—*Elliott supercharger—Power make-up characteristics for various inlet air temperatures*

Control Systems

The combustion and feed water control systems provided positive control of the steam generating system under the automatic, remote-manual and direct-manual control modes, and allowed an easy transfer between these modes. The steam generating system was automatically controlled from the minimum rate of six per cent through the overload rate.

During steady load operations, the automatic control system maintained the air/fuel ratio at values similar to those obtained under the remote-manual mode and held steam drum pressure within 3 lb/in² of set point. Water level was maintained within ± ½-in of normal.

During manœuvring operations the response of the system was excellent. Rapid manœuvres were conducted between 10 and 90 per cent of full power in 25 seconds. During upward manœuvres, steam drum pressure was maintained within 100 lb/in² of set point and water level within four inches of normal. Downward manœuvres were conducted without smoking while maintaining drum pressure within 25 lb/in² and water level within four inches of normal. Recorder charts for some typical manœuvres are shown in Fig. 18 (a and b). The automatic combustion control system as used for these ships is shown in Fig. 19.

Lighting-off

Normal light-off was conducted using the first stage of all three burners at the fuel pump supply pressure of 550 lb/in² gauge. This provided a fuel rate of 580 lb/h. The supercharger was driven by a clutchable electric motor at 1000 rev/

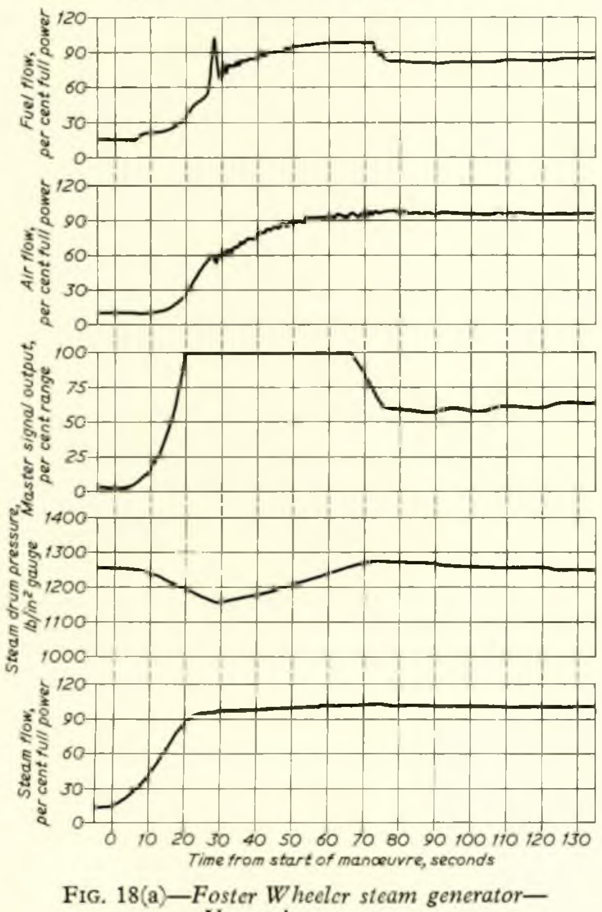

FIG. 18(a)—*Foster Wheeler steam generator—Upward manœuvre*

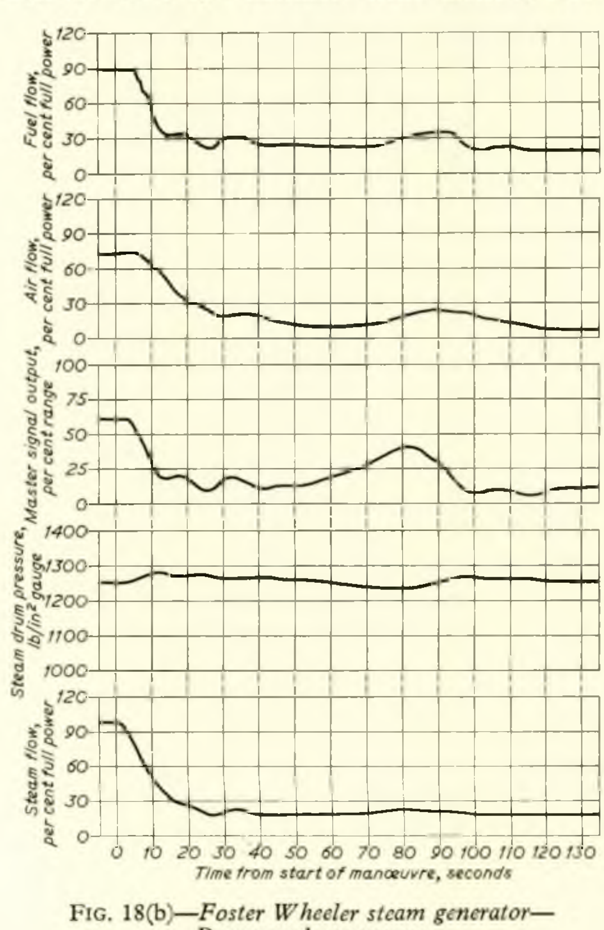

FIG. 18(b)—*Foster Wheeler steam generator—Downward manœuvre*

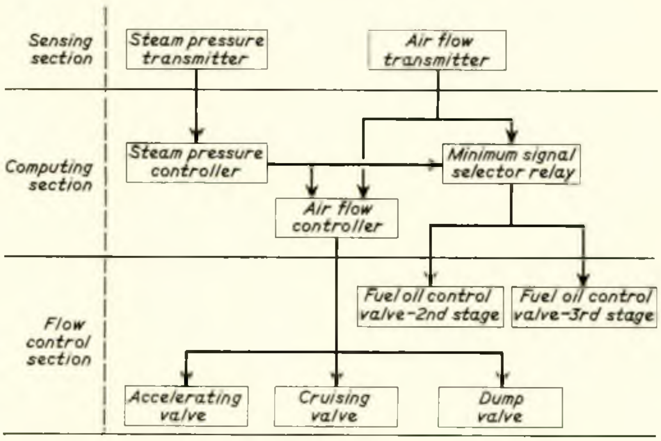

FIG. 19—*General Regulator automatic combustion control system*

min; at this speed, the supercharger provided 12 000 lb/h of air. Using 100 lb/in^2 gauge superheater protection steam, a cold boiler was normally brought up to pressure and placed on the line in 50 minutes; the limiting factor was the air supplied. With adequate external steam available to drive the supercharger at higher speeds, pressure could be raised in an initially cold boiler in 15 minutes by firing at greater than first stage fuel rate. This type of emergency light-off could be conducted without exceeding 1050°F (566°C) final steam or 1200°F (649°C) superheater tube metal temperature.

Extended Steaming Tests

The Foster Wheeler prototype test boiler has been steamed a total of 4500 hours comprising performance as well as extended steaming operations. At least 3000 of these steaming hours were accrued in 100 to 200-h continuous steaming increments. Of the total steaming hours, 400 have been at or above the full power rate. All boiler components have not been exposed to this full amount of steaming since some components were modified or replaced because of the various developmental modifications. The superheater has been steamed for 3500 hours.

The Foster Wheeler production boiler with Elliott supercharger is currently undergoing endurance testing to duplicate shipboard operating conditions. To date, 2500 hours have been completed of the current goal of 8000 hours. In addition to evaluating performance deterioration, these operations are designed to validate operating and maintenance procedures and to provide a basis for collection of component failure rate information.

Shipboard Experience

To date, an aggregate of 15 000 operating hours have been successfully completed aboard ships of the DE-1040/DEG-1/AGDE-1 classes. More than 6000 of these hours were completed on the U.S.S. *Garcia*, the first ship of these classes.

All phases of installation, start-up, trials and operation of these steam plants have proceeded very well considering the significant differences between this and previous naval steam plants. The single area requiring most attention was the indoctrination and education of personnel responsible for various phases of the work. The Naval Boiler and Turbine Laboratory was assigned the responsibility of providing this guidance. Representatives of the shipbuilding yards and naval supervisors of shipbuilding received instruction and operational training at the laboratory. Naval operating crew members underwent a six-week course in the theory, operation and maintenance of the plant at the laboratory and Naval School, Boilermen. Engineering representatives from the laboratory made numerous visits to the initial ships of the class to provide additional guidance.

These efforts were rewarding; primarily, the initial and critical phases were completed with successful and trouble-free start-up and operation. Secondly, a broad base of shipboard experience was developed for application to the later ships of the class. Thirdly, an ever-growing number of personnel with supercharged boiler experience was developed.

CONCLUSIONS

The supercharged boiler has been the most significant change in naval steam generation since adoption of the 1200 lb/in^2 gauge, 950°F (510°C) pressure/temperature standard and, as a revolutionary marine advance, it may be ranked with the recent installations of once-through supercritical boilers in shore power plants.

Evaluation is continuing in endurance tests at the Naval Boiler and Turbine Laboratory and Fleet installations are now in operation. It is anticipated that more definite data will be obtained for forming a comparison of conventional and supercharged steam generators when the units reach the first ship overhaul periods.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Babcock and Wilcox Company, the Elliott Company, the Foster Wheeler Corporation and the Todd Equipment Division for data, information and the use of certain plates presented herein. Mr. D. Paolucci's assistance in preparing certain plates is also appreciated.

The opinions and assertions of this paper are not to be construed as official or reflecting the official views of the Navy Department.

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Discussion

At the Institute Headquarters in London, Tuesday, 9th May 1967

MR. J. H. MILTON (Member), in opening the discussion, thanked the authors for a most interesting and informative paper. Although like many others present he had had experience with boilers of many types, those described so ably by the authors were, so far as he was concerned, very different.

The factors governing the choice of a boiler for naval service were very different from those for the mercantile marine, the actual cost of steam per pound being of little consequence, so long as it was plentiful and its source was small and of light weight.

The quoted heat release rate of 1 400 000 B.t.u./ft^3-h was startling and was about ten times that of a conventional mercantile marine unit; it was a strong indication of the metallurgical difficulties which must have been encountered with furnace tubes etc., also the necessity for very strict attention to feed water purity.

Superheaters, due to the relatively lower heat transfer rate of their inner surfaces and ensuing high metal temperatures, were prone to slagging and metallurgical problems; it was not surprising that these small high output units could apparently only operate on distillate fuels and, also, that difficulties were experienced with superheater tubes and supports.

It was a generally recognized fact that naval requirements had prompted designs which, brought to a practical conclusion by research and development, were subsequently adopted for mercantile use. The present conventional "D" type boilers and turbines of the mercantile marine were typical of naval practice.

As the authors had commented, the concept of supercharged boilers was not new. Velox and Sural developed such units as far back as 1930. Doubtless, however, the tremendous strides made by the aircraft industry in rotary compressors and gas turbines, also the efforts of the metallurgist had made major contributions to the success of the designs discussed.

The present tendency in mercantile marine boiler design was to produce a reliable unit which was less susceptible to slagging and fouling on the gas side, a major factor in maintenance, and the authors' comments on the possibility of producing a reliable supercharged steam generator, operating on boiler oil and free from the aforementioned undesirable feature, would be appreciated. The boiler described was working well within tried pressures and temperatures, circulation was natural and the drum conditions were normal, the use of heavy fuel was the key factor for its commercial application.

There were, at the present time, highly efficient, reliable and compact turbines and epicyclic gearing. If it were possible that comparable developments could be made in the supercharged steam generator field, the resulting installation, by virtue of its compactness and light weight, might well swing the balance in favour of steam over Diesel for main propulsion.

In conclusion he wished to say how much those in this country appreciated hearing about developments taking place in the United States and looked forward to further papers of the same calibre in the near future.

COMMANDER E. M. S. WINDRIDGE, R.N., said that the development of pressure fired boilers had been watched with considerable interest.

Whether it was fair to say that all naval engineers had weight and space engraved on their hearts he was not sure, but weight and space would seem to be a major advantage which the pressure fired boiler offered naval engineers. As had been pointed out, there had been a number of ship designs making use of the pressure combustion principle, but the salient point in the American application of it was the success achieved by the careful programme with regard to overall efficiency and reliability.

From naval experience it would appear that the majority of advantages claimed for a reduction in maintenance would apply equally well to any highly rated boiler fired with distillate fuels.

Reference had been made to film boiling having taken place in the very highly rated tube surfaces due to uneven combustion. Modifications produced a safety margin between the nucleate and the film condition, but it would be interesting to know what safety criterion the authors would propose in the design of that type. It would seem that calculation of D.N.B. ratio, as carried out in a pressurized water reactor type calculation, would be an unwieldy tool in that instance.

Secondly, it was noted that the combustion was improved when air was equitably distributed to the registers. It was appreciated that changes might have been small, but their effect was dramatic inasmuch as the formation of soot was almost eliminated. Could the authors give some information or figures to illustrate the extent of the difference between initial maldistribution and final satisfactory condition?

MR. W. TIPLER, M.A. (Member) said it was both interesting and encouraging that the United States Navy had taken up this particular line of development which was begun over thirty years ago. While naval applications were of interest to countries retaining significant navies, there was probably more concern with the use of similar techniques on merchant vessels or on land. In merchant vessels, weight and volume were still of importance, but not to the same extent as in a naval vessel. On the other hand, first cost and operating costs became of much greater concern.

Operating cost ultimately depended very largely on good design. Of the advantages in reliability quoted in the paper, most stemmed not from supercharging, but from a fresh approach to boiler design. It was not certain that a supercharged boiler would be an economic proposition for a merchant vessel, but a similar fresh approach to the design of conventional boilers, particularly more attention to symmetry, could bring many of the advantages listed in the paper.

The boilers discussed were again at present ruled out from merchant service because they had not yet operated long-term on normal bunker fuels. That was not basically impossible because they were supercharged boilers. Superchargers gave reliable service in heavy fuel burning Diesels. Turbine fouling had occurred, but the methods of combating it were known. Indeed, the case of a supercharger on a boiler was easier, since there was no ash from lubricating oil to contribute to fouling. Concerning the superheater, the supercharged boiler had the advantage that high rates of heat transfer could be obtained without high gas velocities. Ash impingement on the tubes would, therefore, be reduced.

It was evident that the combustion space had been cut to the minimum on the boilers discussed in the paper and that problems had arisen due to a lack of data on the radiation from pressurized flames. It would be interesting to know whether the United States Navy were backing up that interesting development with research programmes aimed at obtaining the fundamentals of combustion and heat transfer under pressure.

On land, the use of supercharging would enable the maximum outputs of packaged boilers to be raised beyond present levels without creating problems of transport—an important factor for an exporting country.

It would, therefore, appear that the influence of pressure on combustion and heat transfer should receive detailed attention in order to support such development. With such data to hand, Mr. Tipler felt confident that a supercharged boiler to operate on fuel oil, without fouling, could readily be developed.

MR. V. TAEGER said that the design of the Foster Wheeler supercharged boiler could not be extrapolated as it stood, either up or down, for example, if it were desired to get twice the output, it would not be possible to take the present design and produce, say double the size, as would be the case for present boilers. Each design would have to be developed for a given output. In other words, at the moment, if anybody asked Foster Wheeler to supply a supercharged boiler, it would be to the design outlined in the paper.

The cost difference against present boilers had, as far as could be seen, for the moment, put them out of court for European navies, unless there was a change in government attitude towards defence. Costs were being watched carefully particularly from the point of view of material and fabrication developments. It was possible that some of the materials now being developed for land boiler superheaters could make a significant price reduction. They were less susceptible than present materials to the stress corrosion problem for instance. Other developments were also being watched with a view to cutting costs.

To reply to an earlier speaker on the question of the mercantile marine and streamlining the design of boilers in general, it was probably true to say that his Company, as designers, would be delighted to carry out developments, but found that shipowners, when approached with any change in design, tended to become very apprehensive and wanted to know who had used the system, where, how long etc. Therefore, they had not had success in that kind of enterprise. Now and again it was possible to get a small change introduced, but shipowners did not generally welcome change.

Again in answer to a previous speaker and concerning package boilers, from what had been done so far, the cost of the gas turbine would probably outweigh the cost of the boiler.

MR. A. F. HODGKIN (Associate Member) said that the authors had concluded that the supercharged boiler was the most significant change in naval steam generation since the adoption of the 1200 lb/in^2 gauge, 950°F (510°C) standard. That might well be so in the United States, but in this part of the world the most significant change was a reduction in naval steam generation. The current trend was towards gas turbine propulsion so that the steam engineer had to consider other fields of application for supercharged steam generators. Steam at sea in ordinary commercial practice was still necessary in large quantities, even though Diesel drive became popular for even larger sizes. Tankers in particular still required a large steam generating capacity to supply the cargo pumps and tank washing equipment. On a Diesel tanker steam at sea was supplied by the exhaust gas boiler, so that that type of vessel would benefit considerably from any development aimed at reducing size, weight, cost and electric power requirements of the pumping boiler. Supercharged steam generation could be such a development.

The method of supercharging described by the authors made use of a gas turbine driven compressor operating at a pressure ratio of 4½ to 5, and each set of that type would be suitable for only one specific boiler design duty. To cover the whole range of outputs required from pumping boilers on tankers (say 45 000 to 200 000 lb/h) would demand a large number of supercharger sets. To establish those from the few sizes already existing would involve the expenditure of some millions of pounds in development work. That would not be absorbed by the available commercial market. In addition, the unit discussed in the paper was largely restricted to distillate fuel which was a serious bar to commercial application. Fortunately, those difficulties were not inherent in all forms of supercharging.

All modern Diesel propelled tankers were fitted with supercharged engines, the superchargers being simpler versions of those used by the authors and existing in a range of standard sizes large enough to cover a wide range of outputs. Those superchargers normally operated at pressure ratios of up to 3, but there was an advantage in operating with a low pressure ratio of, say, 1·5. In those circumstances, it was not difficult to construct a boiler of orthodox pattern with casings strong enough to withstand the air and gas pressures involved. They were, in fact, within the scope of those considered for the latest conventional naval boiler. As a result, not only was the supercharger itself a well tried item, but the boiler design was not extrapolated beyond present experience. Also, the fuel can be taken from the normal ships' bunkers.

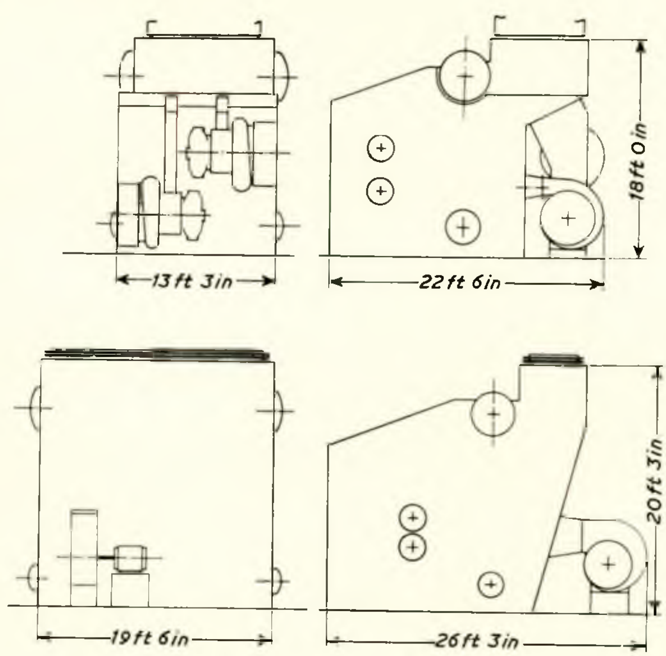


FIG. 20—*Comparison between a naturally aspirated and a supercharged unit*

Fig. 20 showed a comparison between a naturally aspirated and a supercharged unit, each designed for maximum evaporation 140 000 lb/h; S.O.P. 400 lb/in^2 gauge, S.O.T. 500°F (260°C) and feed water temperature 220°F (104°C). The naturally aspirted boiler was of standard M.11 type currently in use in many tankers. The supercharged boiler was a scaled down version of the same type having, of course, the addition of supercharging equipment instead of the forced draught fan applicable to the conventional boiler. In the present case, two standard supercharger units were shown, each operating with a pressure ratio of a little over 1·5. The boiler unit had a fairly low resistance, so that there was excess power from 50 per cent load upwards. That unit was designed to meet four specific outputs, two above and two below 50 per cent. At the higher loads the unit operated as a self-sustaining supercharged system. For starting up and for low load operation, an electric fan was provided, discharging into the compressor inlet. A superheater was situated in the uptake of each unit.

hours a year. That was very good, but a great amount of data was also produced. It meant of course that there were many things which the authors had not been able to include in the paper, so that they really knew rather more than they had said.

Previous speakers had referred to the question of maintenance. He was not convinced that the authors had made out a case that there was a reduction in maintenance due solely to the boiler design. He did not wish to pursue the advantages due to burning distillate fuel, as this had already been raised by previous speakers.

He felt somewhat of a heretic on the question of reducing size. It was realized that everyone said that size and weight must come down, and efforts were being made to achieve this, but he had to take the boiler to sea and, if it were too small and he could not get into it, he was suspicious. He liked a balance between size and maintainability and accessibility, and asked the authors whether they had really achieved it.

TABLE III

	Naturally aspirated			Supercharged		
	Absorption Btu/ft^2-h	Mass velocity lb/ft^2-h	Total draught loss, per cent	Absorption Btu/ft^2-h	Mass velocity lb/ft^2-h	Total draught loss, per cent
Casings	—	10 000	3·2	—	20 000	4·5
Burner	—	—	75·0	—	—	52·0
Furnace	82 000	—	—	110 000	—	—
Screen	29 800	2010	1·8	35 800	3940	4·0
Main bank	11 200	3580	9·0	20 000	6940	29·0
Superheater	5650	7775	11·0	5650	7775	10·5
Heat release, Btu/ft^3-h	125 000			328 000		
Weight wet tons	87			63		
Box volume, ft^3	10 350			5360		
Electric fan, hp	167			45		

Table III showed, in a manner similar to that used in the paper, data applicable to both designs.

The advantages of the supercharged system were of similar kind to those shown in the paper and, although smaller in degree, were sufficient to warrant careful consideration.

MR. G. H. STEWARD said that the measurement by the authors of heat flux of 260 000 Btu/h-ft^2 was most interesting. He wondered where in the tube thickness the temperatures were determined and whether, in point of fact, there were any local disturbances at any point that gave rise to the burn-out conditions, or whether it was a question of internal scale or circulation factors that were perhaps a little on the low side.

The arrangements of the boilers were interesting and one wondered why natural circulation was chosen, since one would have thought that the inherent flexibility of forced or controlled circulation would enable overall volumes and weight to be reduced still further.

Incidentally, perhaps the stress corrosion problem could have been alleviated by using some of the 9 or 13 per cent chrome ferritics rather than austenitics.

COMMANDER V. EVANS, R.N., said that in the sort of running trials as carried out by the authors, it was very difficult to present the complete results adequately on paper. He had been impressed because his officers at the Admiralty Marine Engineering Establishment were often faced with the problem of getting an adequate amount of data into a small report. The paper informed the reader of results of ten years of trials, and it appeared that the current rate of testing was over 2000

It would be interesting to have more information about the Babcock and Wilcox generator, because from the drawings in the paper, it appeared to be a much more difficult furnace to burn in as a result of the way it was set out. The Foster Wheeler boiler was provided with three burners which fired downwards towards a refractory plug about eight feet away. The Babcock and Wilcox boiler showed only two burners which were stated to be identical. From the stated steam take off of 148 100 lb/h, he calculated that each of these burners had to provide about 5700 lb/h of fuel and 90 000 lb/h of air. This had to be achieved when firing horizontally towards what appeared to be a welded water wall only about five feet away. It was to be hoped that there would be available some results of the Babcock and Wilcox trials at some stage.

Referring to the question of registers and intensity of combustion, it would be helpful to know more about the process of pressure combustion. As a result of some measurements which were made, it would appear that the Todd burners used in both boilers were about the same size in exit cross-sectional area as the present Admiralty burners. It had been necessary in designing the Admiralty register to try and get the burner size down in dimensions and it would appear that, in order to be able to get the burners on the small Foster Wheeler supercharged boiler within the limitations of a three feet diameter plate, it was necessary also to keep those registers small.

In the paper there was reference to 2 lb/in^2 drop across the burner, which was quite a lot. In Admiralty registers with similar mass flux density it was about 0·5 lb/in^2. It would be of interest to know whether the improvements in furnace heat release rate were due to the concentration of the oxygen, the degree of air pre-heat, or whether the register had anything to do with it. Perhaps the authors would comment on how much the register contributed. The Todd burner appeared to do very well. Did that mean that one could reduce the current conventional furnace size with a good burner to get the heat release rates up without any damage, or could the supercharged steam generator furnace size be reduced if a smaller register with a higher mass flux density were used.

MR. R. E. ZOLLER, B.Sc. (Member) made a verbal contribution at this point, An extended and more detailed version of his contribution now appears in the Correspondence section of the discussion.

MR. R. BURROWS said that there were two points on which he desired more information. The first concerned the selection of operating conditions for the units described. It was suggested by an earlier speaker that possibly for mercantile use one might use lower supercharging pressures. It would be interesting to have some idea of how the particular gas pressures were arrived at.

It was noticed that a limitation was imposed on the starting-up by the available electrical power to run the superchargers. It would be of interest to know whether any consideration was given to the possibility of firing oil at the boiler exit to the gas turbine during the start-up in order to get more power out of the superchargers earlier in the process.

Correspondence

CAPTAIN R. M. INCHES, R.N. (Member) wrote that when he was last in touch with this project, the components had all been proved separately as far as possible, but it still had to be established that the various characteristics could be made compatible, over the very wide range required, in automatic control. This looked no mean task. He was very happy to know that it had been achieved so successfully.

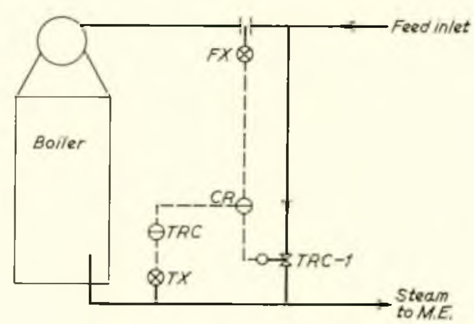
It was only reasonable that a steam generator of this type should use distillate fuel and it was very encouraging to learn that Navy Special could also be used. He would be very interested to know whether the limit of 75 per cent full power with that fuel was arrived at from calculations of likely radiant heat transfer, or practical experience with air requirements, or perhaps something else altogether.

As regards the construction, clearly welding played a vital part. However, it was not clear to him, to what extent this method had been used for joining tubes to headers. He would be grateful if the authors could say something about this.

The authors referred to two procedures for bringing the generator "on the line", of which they called the slower one "normal". There was considerable evidence—some of it even in the paper—that the thermal gradients during this part of the operating cycle created stresses which were unusual, both in their magnitude and in their direction. Since the maximum temperatures remained within the acceptable limits, even during the more rapid light-off, there seemed, therefore, to be a case for making the more rapid one the normal procedure. The slower would still have to be used when there was no external steam supply, but this situation seemed to occur rather less often now that it used to.

Finally, he would be very glad to know whether there was any intention to establish how the plant would react to the use of residual fuel which had been washed and purified, observing the great reduction in the normal residual fuel problems which this treatment had produced in other highly rated units.

MR. I. J. DAY (Associate Member) commented, in a written contribution, that he noticed from Figs. 18(a) and 18(b) that no reference was made to the final steam temperature. It would be interesting to know how this fluctuated with such violent manoeuvres. He could find no reference to any controls for the superheat temperature and, since one would expect this to vary considerably in a boiler of this flexibility, especially for warship use, it would be interesting to know if such temperature variations were acceptable to the turbine designer and also to the rest of the plant. If, in fact, a superheat control system was not fitted, he would make the following suggestion, the drawbacks of which, no doubt, his friends in the control industry would point out. The scheme was an anticipatory one, based on feed flow, and would maintain the superheat outlet temperature at a more constant level than one based on pure temperature.



FX *Flow transmitter*
CR *Computing relay*
TRC *Temperature recorder controller*
TX *Temperature transmitter*
TRC-1 *Final steam temperature control valve*

FIG. 21—*Anticipatory temperature control scheme*

The scheme was illustrated in Fig. 21. The computing relay CR would be of the form:

$$P = \frac{100}{G}(A - C) + K$$

where G = 100 per cent
and K = 9 lb/in^2

and it was the setting of this, together with the careful calibration of orifice plate which would ensure the success of the loop. One would assume that the feed flow measurement for the feed controls mentioned by the authors was accomplished by means of an orifice plate and, depending upon its calibration, it should be possible to utilize this. As could be seen, the feed flow dictated the initial setting of the desuperheating valve and the proportional plus integral temperature recorder controller TRC adjusted it as the final temperature settled down. It would appear impractical to fit gas bypass dampers around the superheater on this boiler and, in any case, it was the authors' experience that the use of these could lead to a reduction in the CO_2 figures, at certain positions, probably due to the differing air flow resistances around and through the superheater. A drawback to the system was that it would be necessary to exercise care during start-up, due to the integral action of TRC, which could cause hunting of the desuperheater valve. Hand control during start-up should not be inconvenient for this.

MR. R. E. ZOLLER, B.Sc. (Member) said, in his enlarged contribution, that in certain applications the advantages of pressure combustion were many, but this paper had weakened the case by claiming many features as exclusive when they also applied to the standard unit. For example, pressure casings must be made tight and any leakage was more unpleasant than under atmospheric conditions, but casings had been damaged in action. Standard units could be erected in the shop and many had been put into the ship in one piece. Some navies, including that of the U.S. had spare boilers for each class. Many superheaters for standard boilers were designed to be removed in one piece, and the casings could be opened in more yards than with the pressure design, where the cutting of a large panel in a pressure vessel required greater skill.

Standard boilers also had automatic control. The starting-up programme was seldom determined by pressure raising, but by turbine temperature limitations, and the inclusion of superheat control would shorten the starting-up procedure more than the supercharged feature. Manœuvring was also limited by steam temperature variations. The tests at Philadelphia on the Babcock and Wilcox unit equivalent to Fig. 18(a) caused the initial temperature of 900°F (482°C) to drop quickly to 830°F (443°C) and then rise to 975°F (524°C) before stabilizing at 960°F (516°C). The trials corresponding to Fig. 18 (b) caused the steam temperature to drop from 980°F (527°C) to 875°F (468°C). Many turbine manufacturers would be alarmed at these violent temperature swings.

The weight and space comparisons under "Reduction in Space and Weight" were also biased, for example, 20 years ago a boiler for identical power was designed with an overall height of 18 ft, an overall width of 17 ft and an overall length of 11 ft 1½ in, giving a box volume of 3400 cubic feet and it was difficult to reconcile the value of 6340 given in this tabulation. The weight of this unit was 39 tons and, possibly, if it were designed for 1200 lb pressure instead of 600, it would have weighed about 47 tons, without a fan, compared with 84 tons in this paper.

The figures in Table I for the conventional boiler did not compare with European practice. For example, the draught losses through the casing burner and boiler might be four per cent, 43 per cent and 32 per cent respectively, while additionally an economizer would require about 21 per cent.

Returning to Fig. 18(a), it would appear from the air flow curve that, between 25 and 70 seconds, there was sufficient air flow to burn the fuel. In the same way, throughout the whole of the downward manœuvre in Fig. 18(b), the air flow in the second curve was substantially less than that required to burn the fuel given in the top curve.

The curve of draught loss for the Babcock and Wilcox boiler shown in Fig. 5 was given in Fig. 22 and, as this was less than specified, the range of power, over which there was excess blower power, was wider than that given in Fig. 17. In addition, the gas turbine had more power as the gas temperature leaving the boiler was rather higher, being near the highest limit of the permitted zone, as shown in Fig. 23., but being nearer the maximum allowable temperature entering the blower, would reduce the time that the boiler could operate with inferior fuel. Alternatively, the maximum evaporation might be restricted. The claim that a high gas pressure improves the cleaniness was hard to reconcile.

It was difficult to understand why so many features had been sacrificed to get perfect symmetry in a pressure-fired boiler, which did not fit the usual boiler-room space. Vertical firing and bottom access increased what was usually the most important dimension, namely height. On the other hand, a change from natural circulation to a form of assisted circulation, when combined with pressurized firing, would, for example, permit a boiler to be installed under a very low deck; this, in some installations, might be an overriding consideration. The fact that this comprehensive test programme had shown pressurized firing to be reliable had given naval architests a possibility of lower decks.

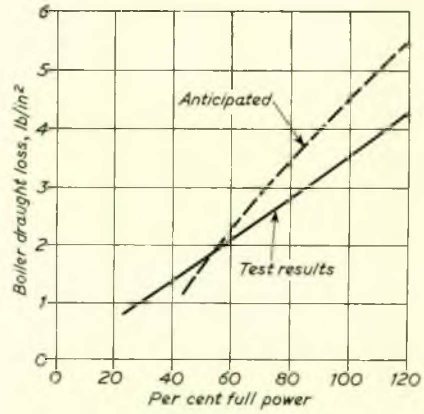


FIG. 22—*Draught loss: Babcock and Wilcox supercharged boiler performance*

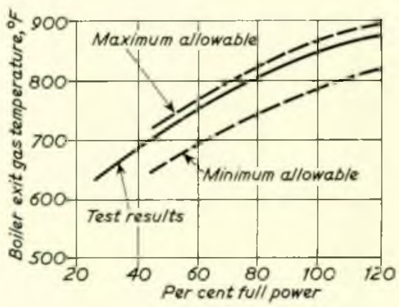


FIG. 23—*Boiler exit gas temperature: Babcock and Wilcox supercharged boiler performance*

Authors' Reply

It would seem that three topics had been raised or implied more often than any others by the contributors. These were the economics of the supercharged steam generating system, commercial application of this system, and the use of residual versus distillate type fuels. Because these topics could form the nucleus of discussion for many separate papers, they would be referred to only insofar as was required to answer specific questions and statements. The authors did feel that steam would continue to be a most competitive and reliable source of power for propulsion of both commercial and naval ships. This fact was based largely on the proven versatility and dependability of steam plants and their ability to operate for extended periods of time on low grade fuels. To this end the experience gained with the pressure fired boiler would prove invaluable in future generations of boiler design, either of the supercharged or conventional type. Dependent upon the types of fuel to be used in the future as a result of current explorations concerning distillate fuels for naval boilers, the pressure fired boiler might very well become a highly competitive type steam system.

Concerning Mr. Milton's comment that metallurgical difficulties must have been encountered, it should be noted that there had been no need for any very extensive improvements from the metallurgical standpoint regarding the boilers. The furnace and all generating tubes were of the normal carbon steel material used in conventional naval boilers. The superheater tube materials were the same. Perhaps the greatest deviation from conventional boilers in this area would be in the welding and quality assurance requirements. Boiler water and feedwater treatment and care and boiler blowdown procedures had all continued to be in accordance with the requirements for 1200 lb/in^2 gauge boilers. Concerning Mr. Milton's request for comments relative to a supercharged steam generator which would operate satisfactorily on boiler fuel, it was believed that this development could be accomplished. Originally, there had been test plans for exploring this possibility. However, because of indicated interest in using a distillate fuel for all boilers, and also because no logistical problems had occurred with the present supercharged boiler ships, exploration into burning a heavy fuel had been deferred.

Commander Windridge's question concerning furnace tube design could only be answered by stating that satisfactory conditions were determined as a result of the test programme and data obtained. As had been pointed out, a turbulator installed in the affected tubes also corrected the adverse conditions. This type of solution was not followed because the turbulator would have prevented mechanical cleaning of the tubes. Concerning combustion problems, the amount of air maldistribution which caused incomplete fuel combustion was not measured within the limits of experimental accuracy. However, it was estimated that one burner received approximately ten per cent. less air than stoichiometric requirements. Even though the total air flow supplied to the boiler was five to ten per cent in excess of stoichiometric requirements, combustion would not be completed in the area below this burner because the rather direct route through the furnace, from burner to screen, resulted in a degree of stratification.

In reply to a question from Mr. Tipler, the authors knew of no programme undertaken by the United States Navy aimed at obtaining fundamentals of combustion and heat transfer under pressure applicable to the pressure fired boiler. The authors agreed with Mr. Tipler's observation that a fresh approach to boiler design should also be applied to conventional boilers. Of the design features applied to the supercharged boiler, many were now being adapted to conventional boilers. These included:

1) down or side firing;
2) more attention to symmetry;
3) welded furnace wall tube construction;
4) a great reduction in the amount of refractories used;
5) prefabrication, rather than field erection, of many components.

The authors took mild exception to Mr. Taeger's comment that the present design could not be extrapolated. It could certainly be extrapolated downward by 20 or 30 per cent by leaving it exactly as it was and one would still end up with a compact boiler producing 80 000 to 100 000 lb/h steam. Upward extrapolations of more than ten per cent might prove difficult because of film boiling which might result in the radient heat absorbing surfaces of the furnace. This extrapolation might, however, be extended with higher temperature feedwater. Current supercharger designs (General Electric and possibly the Ingersoll Rand) could handle up to 15 per cent more than the current maximum firing rate without modification.

The quasi-supercharged boiler design proposed by Mr. Hodgkin was quite interesting and certainly merited further consideration because many of the size and efficiency advantages might accrue from a relatively small departure from conventional design practices. Mr. Hodgkin should, however, consider the benefits (uniformity of heat absorption and simplicity of casing construction and maintenance) to be gained by the symmetry of a cylindrical boiler.

Mr. Steward had inquired into the techniques used in measuring heat absorption. The peak value of 260 000 Btu/h-ft^2 was a design figure for portions of the furnace tubes which absorbed a large degree of radiant heat and was not validated by test. The method generally used to determine absorption, however, involved solution of a gas to water/steam heat balance based on temperature, pressure, and flow measurements of those fluids. A considerable amount of tube metal temperature measurements had been made to determine the operating safety margin of particular tubes. These measurements were considered to determine accurately surface metal temperature to within 0·010 in of the surface of tubes. The wall thicknesses of which varied from 0·095-in to 0·120-in. Mr. Steward also suggested the use of nine or thirteen per cent chrome ferritics to eliminate the superheater stress corrosion problems encountered. Such materials could not be used, however, at the 1100°F (593°C) temperatures encountered in 1250 lb/in^2 gauge 950°F (510°C) superheaters. In multi-pass superheaters, a 2¼ per cent chrome ferritic was used in the earlier passes where the service temperatures were lower. Even in this application, the 2¼ per cent chrome was superior to the nine or thirteen per cent chrome ferritics because of superior formability and air hardening qualities. Perhaps one of the most important reasons for not choosing forced circulation was the factor of introducing two new major boiler concepts into the service at one and the same time.

The authors did not feel that this plant had been designed for minimum size and weight at the sacrifice of accessibility and maintainability features as suggested by Commander Evans. Weight, in fact, was not considered to be a major consideration of itself but was a natural outgrowth of the compact design. It was felt that an optimum balance had been achieved between size and maintainability. Furnace tubes, burners, refractories, superheater supports and watersides were readily accessible. The majority of the accessibility problems experienced to date had resulted from less than perfect installation arrangements aboard ship. Any future steam generator designs would of course include minor changes to improve access and maintainability. Commander Evans proposed that burner register design might contribute to the increased furnace heat release rates achieved in these generators. However, the heat release rate resulted from the gas pressure and furnace volume selected in the design. The register design then was that which was necessary to insure complete combustion of the fuel within the furnace.

Because the question of maintainability had been referred to before, it seemed appropriate to comment upon Commander Evans' remarks concerning that subject. The authors concurred that one of the reasons for reduction in maintenance requirements was the fact that distillate fuel was used. However, other reasons included:

1) reduction in size which should, if proper lay-out were followed, make accessibility to required areas easier;
2) use of pressure vessel type casing which eliminated frequent casing examination and repair;
3) small unitized construction which eliminated the need for removable casing and access panels.

Mr. Burrows had asked for some additional information concerning the criteria used in selecting gas pressure level. They were based principally on attaining the maximum degree of size reduction, and therefore the maximum amount of supercharging, consistent with certain practical limitations. These were:

1) that convection tube spacing was already reduced to the minimum allowed by header ligament size;
2) that furnace size could not be further reduced without restricting access for maintenance or adversely influencing combustion;
3) that compressor design and power requirements would be vastly increased by further increases in gas pressure level.

Lower degrees of supercharging could of course also result in some significant boiler size reductions. For example, it was estimated that pressure levels in the order of two atmospheres would reduce convection surface requirements by about 25 per cent in certain boiler configurations.

Consideration had been given to firing fuel into boiler exit gas stream for assist power in starting up and during operation as suggested by Mr. Burrows. This particular configuration was not used, however, to avoid unnecessary mechanical complications of the supercharger and because operation of the shipboard plant was already dependent on the availability of electrical power for the feedwater booster pumps and the fuel oil service pumps. The electric starting up motor was rated at 10 hp which was small. The boost turbine was rated at 1000 hp because of the short duration higher power levels needed during accelerations.

Operation of the test boiler with Navy Special Fuel, as questioned by Captain Inches, was restricted to 75 per cent of full power because of gas bypassing in the original test boiler resulting from deterioration of a refractory gas baffle. This deterioration had occurred prior to operation with the Navy Special Fuel. There were no indications that Navy Special Fuel could not be used up to the maximum load in a properly performing boiler. Boiler tube to header joints were rolled as in a conventional boiler. Superheater tubes were welded to nozzles extending from the superheater header as was the case in conventional boiler construction. There was no present consideration being given to the exploration of using residual fuel which had been washed and purified. This was because, as previously stated, that consideration might eventually be given to other fuels for boiler use.

Mr. Day and others had expressed concern over the wide steam temperature variation that might be expected to occur during rapid load changes. In fact, the steam temperature variations were no more severe than experienced in D-type boilers, which was about 100 deg F (70 deg C) change for a rapid downward manœuvre. The turbine manufacturers had accepted and had designed for such conditions, and the authors were not aware of any service problems resulting from such conditions. In the future it might be necessary to consider a steam atemperator similar to that proposed by Mr. Day to limit the maximum temperature occurring during the manœuvre, but not to restrict the magnitude of the change.

Mr. Zoller had made several interesting comments, but these were definitely not in agreement with the authors' information. The size and weight figures given in the paper for the conventional boiler represented the U.S. Navy's DD-931 Class boilers which were 1200 lb/in^2, 950°F, (510°C) non-superheat control, D-type, with economizer. They were typical in configuration, size and compactness to all of the U.S. Navy's post war combatant boilers. The full power main steam rate was two per cent greater than the Foster Wheeler supercharged boiler. The size and weight figures given for this and the supercharged boiler had been checked and were correct. If Mr. Zoller had access to the design of a conventionally fired boiler which compared with the size and weight of the supercharged boiler, he was encouraged to make this known.

Some other comments concerning Mr. Zoller's remarks were:

1) Standard boilers could be shop erected as compared to field erected—the difficulty, though, was in transporting them to the building yard.
2) No combatant D-type boiler in the U.S. Navy had a unitized removable superheater.
3) Arc cutting and rewelding the ½-in steel boiler pressure shell presented no difficulty.
4) Main turbine temperature limitations did not determine the boiler lighting-off time on a ship which was already underway with one boiler. In the case of a combatant ship which required the second boiler on line in a short time during emergencies the rapid light-off feature was quite desirable.
5) The U.S. Navy avoided superheat control in its combatant boilers because of the additional manufacturing, operational, and maintenance complexities which it added to the boilers. Main turbines were designed for and successfully operated with the steam temperature variations encountered with non-superheat control boilers.
6) The curves of Figs. 18(a) and 18(b) were actual recordings made during system manœuvres and were used qualitatively to evaluate system performance during the manœuvre. Because of their speed and the large quantity of channels used for such an evaluation (20 channels in this instance) they did not give highly accurate quantitative data. Based on these recordings, however, Mr. Zoller had concluded that the boiler smoked during upward and downward load changes. There had been no problems concerning smoking during any load changes.
7) Height had been no problem. The boilers fitted quite nicely into the destroyer escort hulls. They were fully below the main deck level, and they forced no change or obstruction to ship compartmentation.

The authors wished to state that they greatly appreciated both the number and the depth of the comments received. The authors would again like to thank the Institute of Marine Engineers for having made the presentation of this paper to their members and guests possible.