Heavy Oil Burning

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The widening use of oil firing in place of coal firing for industrial and marine boilers, together with the steady increase in the applications of the industrial gas turbine, throws into prominence the problems of heavy oil burning. The authors have been engaged in the field of combustion for a number of years, and they present in this paper a study of the most important factors arising in heavy oil combustion problems.

The properties of various fuels are considered with special reference to the requirements of fuel injection and the different methods of fuel atomization. The problems of fuel droplet evaporation and combustion and of carbon deposition form other sections of the paper, and a discussion is given on primary combustion zone flow pattern design and its relationship to the spray.

Two types of combustion equipment are defined—combustors (with enclosed flame) and registers (with open flame), and the special problems of design and performance of these are separately treated. The authors have been associated with the design and supply of air registers both for marine applications and for industrial boilers, and several practical examples of such equipment are discussed and illustrated.

The "stabilized flame" principle, a common feature of all combustion equipment produced by the authors' company, is described, with particular reference to its highly successful application in the form of the "Lancastrian" air register for the conversion of Lancashire boilers from coal firing to oil firing.

INTRODUCTION

Before one can understand the behaviour of a given piece of combustion equipment, or indeed design combustion equipment, it is necessary to consider a wide variety of branches of combustion technology, starting with the properties of the fuels to be burnt, and proceeding through considerations of atomization, evaporation, flow pattern and heat transfer to the design of the final equipment.

The combustion equipment required for the aspects of heavy fuel burning covered in the present paper falls broadly into two classes, combustors and registers, which are dealt with in separate sections of the paper.

The combustor is an enclosed combustion chamber in which the combustion itself is completed, and in some applications a certain degree of dilution of the combustion products is carried out. The register on the other hand introduces the fuel and air for combustion, but does not contain the flame, which is allowed to radiate its heat directly to the furnace walls or to the boiler tubes.

Economic considerations often dictate the use of a residual fuel, but in the present paper both residual and distillate fuels are discussed for the sake of completeness, and the relative difficulty of burning residual fuel is explained.

The paper is subdivided therefore into the following sections:—

1. Physical and chemical properties of fuels.
2. Atomization of liquid fuels.
3. Evaporation and burning times.
4. Carbon deposition.
5. Aerodynamic requirements of flame stabilization.
6. Flow pattern development.
7. Relation of the fuel spray to the flow pattern.
8. Heat release rates.
9. Combustors.
10. Registers.
11. Fuel systems.

Appendix: Instrumentation for gas analysis.

1. PHYSICAL AND CHEMICAL PROPERTIES OF FUELS

It is well known that distillate fuels are more readily burnt than the residuals, but in combustion equipment developed for residual fuels, the flame length is largely determined by the combustion of the carbon cenospheres which are inevitably formed, and to control this, it is necessary to adjust the oil preheat temperature to maintain a sensibly constant viscosity at the sprayer.

The body of experience in the combustion of sprays of a liquid fuel is very much greater in the field of distillates than residuals, and for this reason continual reference is made in this paper to the former. In particular, it is necessary to compare and contrast the physical and chemical properties of the two groups.

Table I shows the relevant properties listed for a variety of fuels ranging from gas oil to bunker fuel oil.

The most important properties from the combustion angle are the specific gravity, calorific value, viscosity, surface tension, aromatic content, carbon/hydrogen ratio, and corrosive constituents such as sulphur and vanadium.

These factors will be mentioned below under the various headings to which they are relevant. Figs. 1 and 2 give data on the viscosity and surface tension respectively for a number of fuels, and show the way in which these parameters are increased in heavy fuels as opposed to the light distillates.

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TABLE I.—PHYSICAL AND CHEMICAL PROPERTIES OF INDUSTRIAL FUELS

	Medium marine Diesel	Marine Diesel	Medium fuel	Heavy fuel	Bunker fuel
Specific gravity	0·840	0·855	0·947	0·955	0·966
Pensky-Martin closed flash point	170	186	218	200	200
Viscosity Redwood No. I at 100 deg. F., sec.	33	37	170	860	3,480
Viscosity Redwood No. I at 120 deg. F., sec.	—	—	—	290	1,400
Pour point, deg. F.	0	0	5	10	<40
Water content, per cent volume	Negligible	Trace	0·05	0·05	<0·08
Sediment by extraction, per cent weight	Negligible	0·01	—	—	—
Sediment by hot filtration	—	—	0·02	0·02	0·05
Neut. value mg. KOH/gm.	0·2	0·6	—	—	—
Colour N.P.A.	1·5—2·0	2·0—2·5	—	—	—
Asphaltenes	0	0	2·0	3·0	3·0
Conradson carbon, per cent weight	Negligible	0·1	7—7·5	10·2	11·5—12
Ramsbottom coke, per cent weight	—	—	6—6·7	8·3	9·5
Sulphur, per cent weight	0·9	1·4	3·4	3·6	4·6
Cetane No.	50—54	45—50	—	—	—
Aniline point, deg. F.	157	147·2	—	—	—
Diesel index	52—56	48—54	—	—	—
Gross calorific value, B.t.u./lb.	19,560	19,500	18,695	18,550	18,440
Ash, per cent weight	—	—	0·02	0·02	0·03
Ultimate analysis C	85·7	85·4	84·8	84·9	84·9
H_2	13·4	13·2	11·8	11·7	11·5
S_2	0·9	1·4	3·4	3·6	4·6
Distillation Range	Deg. F.	Deg. F.			
Initial boiling point	363	428			
Temperature for 20 per cent recovered	464	506			
Temperature for 50 per cent recovered	541	563			
Temperature for 80 per cent recovered	623	628			
Final boiling point	>680	>680			

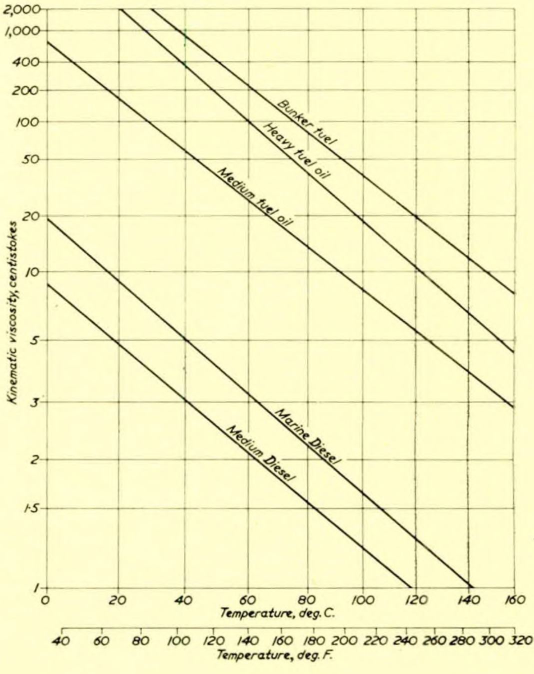


FIG. 1—*Viscosity temperature chart for liquid petroleum products*

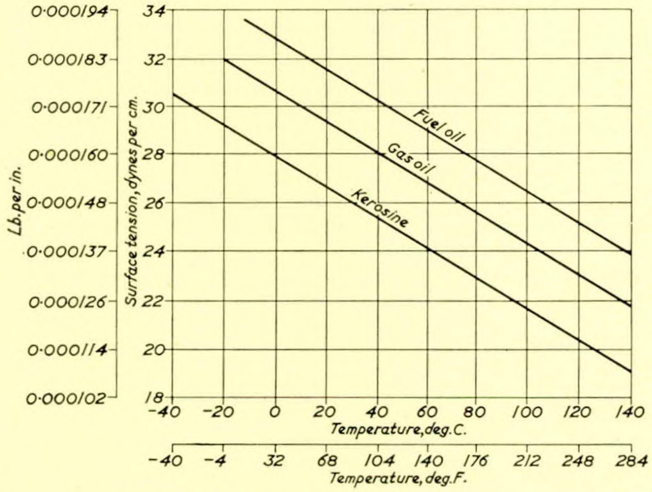


FIG. 2—*Surface tension, temperature chart for liquid petroleum products*

2. ATOMIZATION OF LIQUID FUELS

Droplets can be produced in many different ways by the disintegration of a liquid stream or a liquid sheet. This disintegration process may be brought about by relative motion of the liquid and the surrounding medium, as for example by discharging the liquid at high velocity through a restricting orifice as in the compression ignition engine or by directing a stream of high velocity air against the stream of liquid as in the carburettor.

In rotating cup atomizers, the atomization of the liquid is brought about by the centrifugal forces which cause the disruption of the liquid film into droplets around the rim of the cup.

In swirl atomizers(9) the liquid is injected tangentially into a vortex chamber, from which it is discharged through an orifice with a rotational motion.

Each method has its own peculiar characteristics, but the phenomena are dependent to a greater or lesser extent upon the same physical parameters, namely the velocity v, the density ρ, the viscosity μ, the surface tension s and the thickness h of the liquid stream and the corresponding properties of the surrounding medium. These parameters may be grouped into two independent dimensionless ratios, namely the Reynolds number $\rho vh/\mu$ and the Weber number $\rho v^2h/s$, in terms of which the behaviour of various atomizers can be described.

The mechanism of the disruption of a liquid stream is not yet fully understood. Early work indicated that the Weber number would be the principal factor involved in atomization, but later work suggests that turbulence in the fluid flow plays an important part in the break up. It seems most likely that the radial components of liquid velocity in the turbulent flow overcome the surface tension forces to break away from the main jet. In the swirl atomizer, this effect is enhanced by tangential injection into the vortex chamber, and consequently atomization is achieved more quickly.

The most usual type of atomizer is the swirl atomizer by means of which it is possible to spread out one cubic centimeter of fuel into droplets having a total surface area of 1,000 square centimeters or more. This area per unit volume is known as the "specific surface", and will be referred to below.

A simple form of swirl atomizer is shown in Fig. 3, to

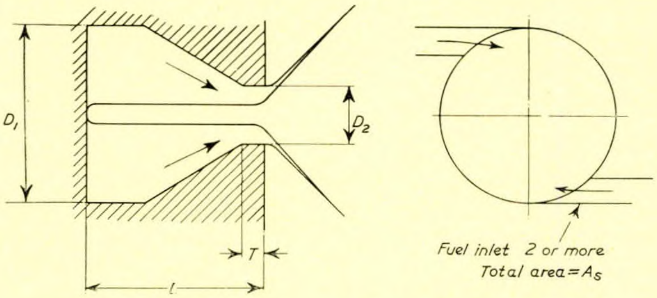


FIG. 3—*Principle of simplex swirl atomizer*

illustrate the principles. Several variants of constructional detail are of course possible. The tangential fuel admission ports may be drilled holes as in the type of atomizer shown in Fig. 4, or slots cut in a plate as in the case of the type shown in Fig. 5.

Fig. 6 shows a normal fully developed conical spray, but when lack of atomizing pressure or other cause prevents the full development of the spray, an appreciable continuous film of liquid fuel exists near the orifice. Though this film appears smooth to the eye, it exhibits ripples in fine structure, as shown in Fig. 7. Droplets may be seen breaking away from the edge of this film, but at lower atomizing pressures still the film would fail to break up, and atomization would cease entirely.

The flow characteristics of such an atomizer may be calculated theoretically on the assumption of irrotational free vortex flow of a non-viscous liquid in a conical swirl chamber. By this means it has been concluded that the discharge coefficient and cone angle should each be expressible as a function of a single dimensionless coefficient A_s/D_1D_2 called the atomizer constant, where A_s is the area of the tangential entry holes, D_1 the diameter of the swirl chamber, and D_2 the diameter of the exit orifice. The atomization of the spray from a swirl

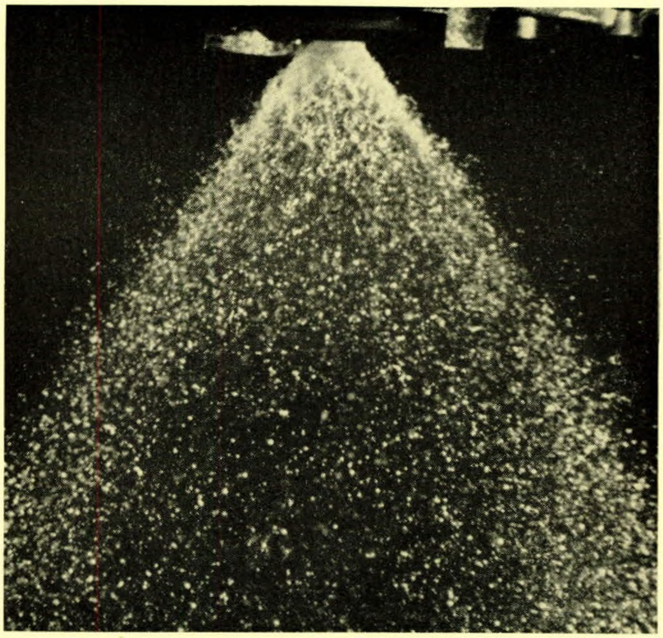


FIG. 6—*Fully developed conical spray*

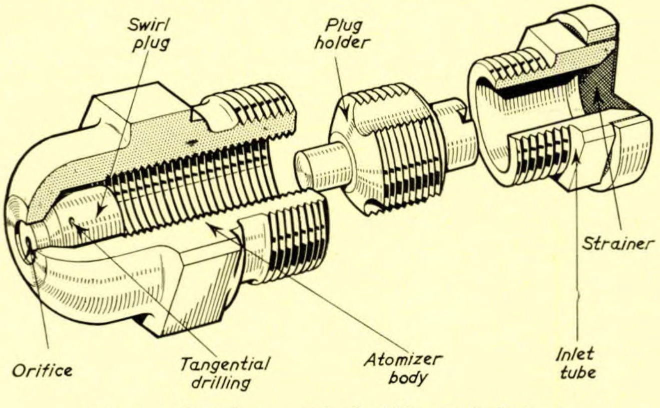


FIG. 4—*Atomizer and body (dismantled view)*

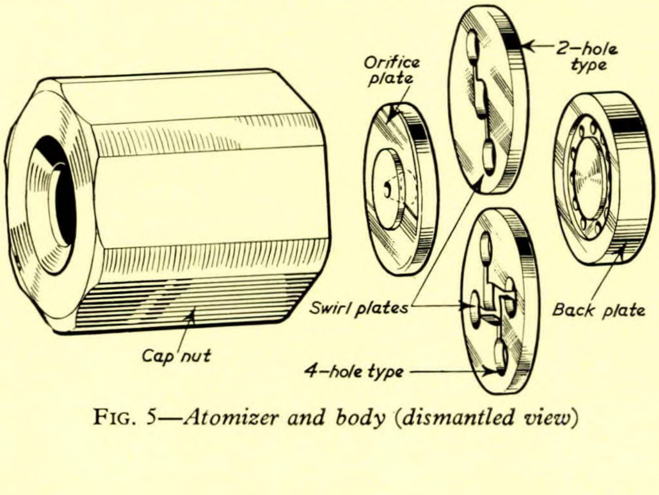


FIG. 5—*Atomizer and body (dismantled view)*

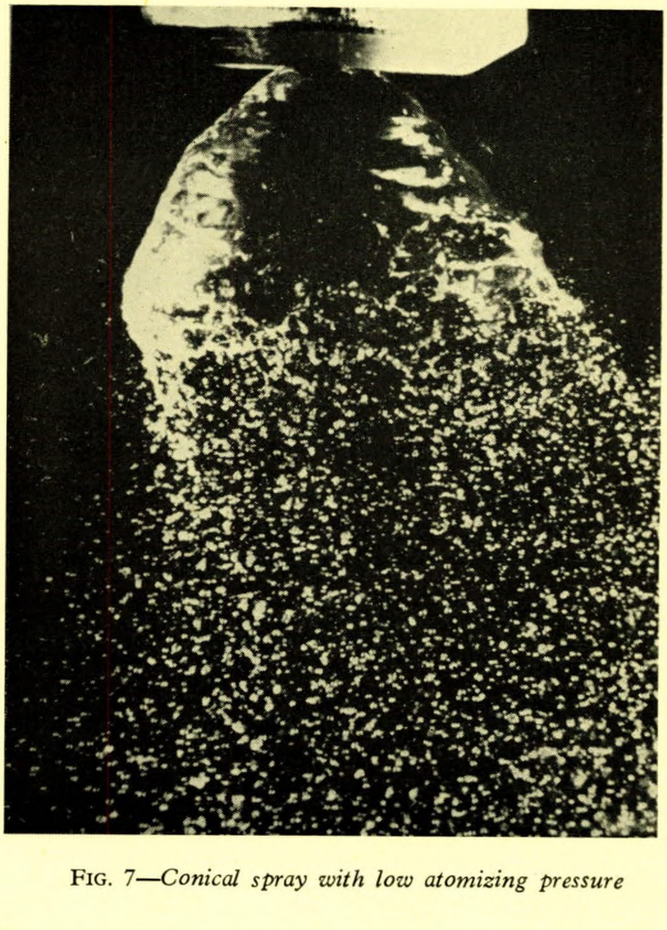


FIG. 7—*Conical spray with low atomizing pressure*

atomizer is felt to be due to microturbulence in the vortex chamber, the chief function of the chamber being to distribute the droplets. Therefore, in considering the droplet size it is only necessary to take into account the physical constants of the liquid being sprayed together with a size representative of the atomizer, while surface tension effects will also be sensibly constant.

Changes in the coefficient of discharge with changes of fluid viscosity can be explained as the result of friction losses in the atomizer. Friction decreases both the tangential and axial velocities. The decrease in tangential velocity will mean a decrease in the swirl, and hence a decrease in the diameter of the air core, so that the effective area of the orifice will become greater. This effect is offset by the reduced axial velocity and, in some cases, is more than offset. It is therefore impossible to generalize on the effect as both increases and decreases can occur. However, there is a limitation on the amount of reduction of the air core so that increasing viscosity will ultimately bring about a reduction of output.

Unlike the spinning cup, the ordinary process of pressure atomization yields a large range of droplet sizes. Fig. 8 shows a cluster of droplets collected from the spray from a simplex atomizer. Droplets may be seen here covering a size range of many thousands to one by volume.

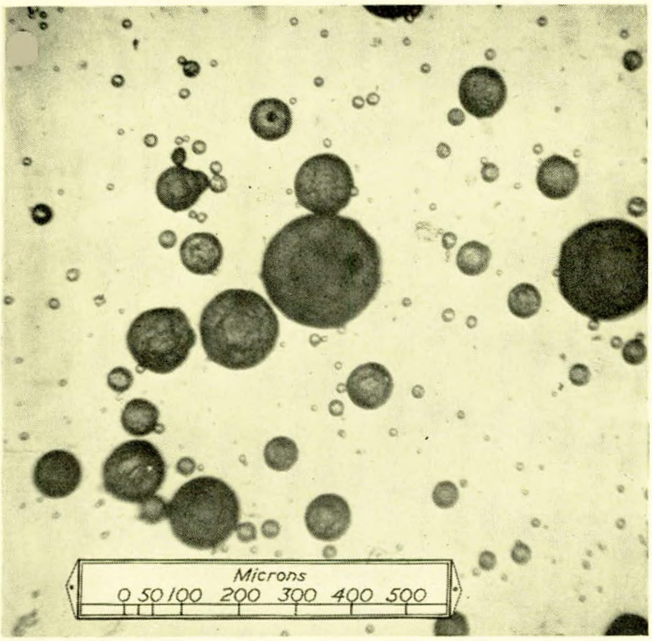


FIG. 8—*Cluster of droplets from simplex atomizer spray*

The usual criterion for the degree of fineness of atomization is the Sauter Mean Diameter (S.M.D.). This is the diameter of the droplet whose specific surface is the same as that of the spray as a whole, the specific surface being defined as already mentioned above. In referring to the S.M.D. of a spray, however, it must not be forgotten what a large range of sizes is represented.

The distribution curves of measured droplet size are found to follow approximately a Rosin-Rammler law, and the Sauter Mean Diameters for different atomizer sizes and pressures are found to satisfy the following equation:

$$S.M.D. = 335\, P^{-0{\cdot}348}\, F^{0{\cdot}209}\, \nu^{0{\cdot}215}$$

Where P is the pressure drop across the atomizer (lb. per sq. in.), F the flow number of the atomizer ($=Q/\sqrt{P}$), ν the kinematic viscosity of the fuel (c.s.) and Q the fuel flow in Imperial gal./hr. Fig. 9 shows a graphical plot of this formula for a certain value of viscosity, and the equation has been verified experimentally for viscosities ranging from 2 to 15 centistokes.

There is little factual evidence to show the effect of ambient air pressure on the droplet size produced by a swirl atomizer. From observations it is known that there is a definite effect, for, on depressing the chamber pressure below atmospheric, the break up of the spray is delayed to a point some way in front of the atomizer. The cone angle also tends to widen and the droplet size to increase. Conversely, an increase in air density assists in atomization up to a density represented by an air pressure at room temperature of about 350lb. per sq. in., after which the atomization becomes coarser.

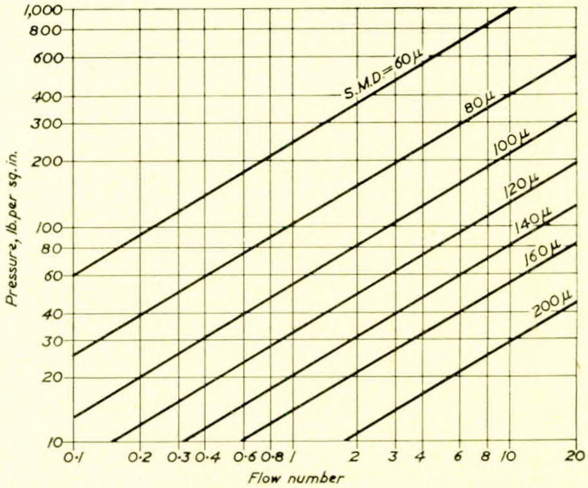


FIG. 9—*Sauter mean diameter v. atomizing pressure and flow number*

In the case of the rotating cup atomizer, the surface tension of the liquid appears to be the prime factor affecting the degree of atomization. This type of spray consists of a remarkably uniform drop size on light loads. Fig. 10 shows an example of a spinning cup atomizer together with its driving motor. This has applications for the atomization of very low fuel flows where the corresponding simplex atomizer would be so small as to give manufacturing and filtration difficulties. Fig. 11 shows a diagrammatic arrangement of a duplex type of spinning cup.

Yet another type of sprayer is the impinging jet type. In this, two streams of liquid are directed at one another at high velocity, so producing a flat spray. The accuracy neces-

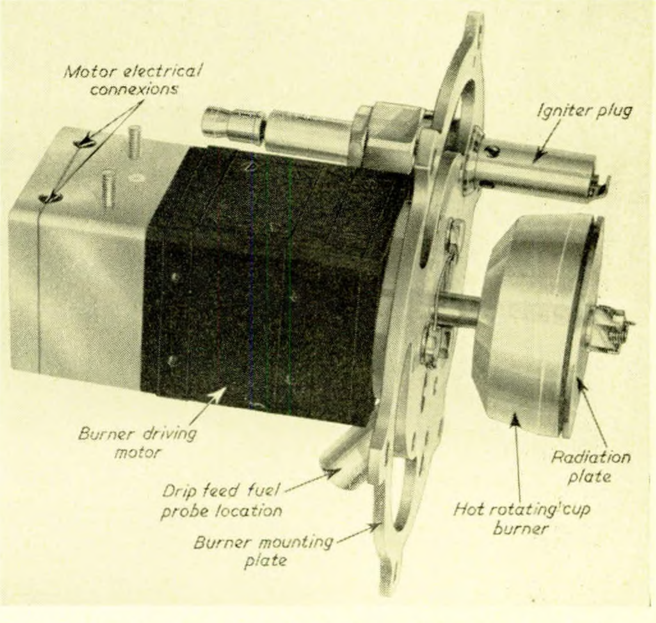


FIG. 10—*General view of rotating cup burner and igniter*

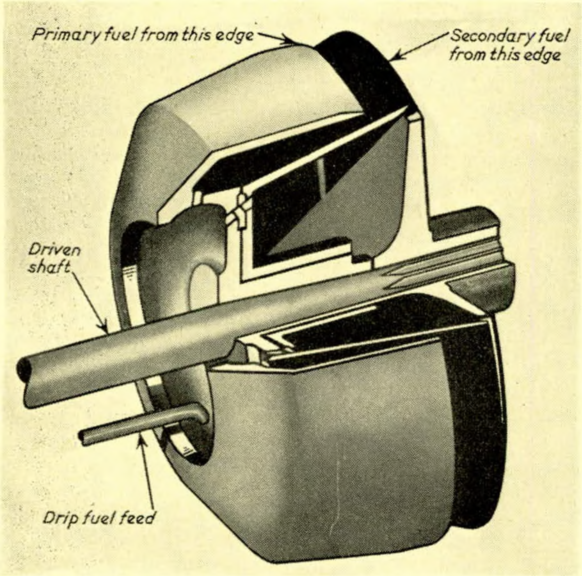


FIG. 11—*Duplex spinning cup atomizer*

sary in the manufacture of this type is very high. In general, it produces a mean droplet size slightly larger than the equivalent swirl atomizer except for flow numbers below about 0·85, when the reverse becomes true.

Having considered the fundamental principles of liquid fuel atomization, the specific problems of atomizing heavy fuels, as applied, for example, to the process of steam raising in boilers can now be considered. The first essential is to determine the requirements in terms of droplet size, spray cone angle, etc., and then to discuss the means of achieving this.

In the case of boilers with registers, it is usual to depend for heat transfer to the tubes to a great extent upon direct radiation from the flame. In the case of a boiler fired by solid fuel, this is obviously the state of affairs, and, as the majority of boilers were originally designed to take solid fuel, it follows that the liquid fuel burning must produce a highly radiant flame in order to give efficient working. The aim, therefore, in burning heavy oil in these circumstances is to produce a mass of radiant carbon particles, occupying a large percentage of the combustion chamber volume. The residence time must be so adjusted that no unburnt carbon passes into the flue, and at the same time unburnt carbon must not come into contact with any surface of the combustion chamber. This means that the droplet size must be carefully controlled at all operating loads.

Experience gained in recent years has suggested that the upper limit of droplet size acceptable for these applications should be of the order of 100-130 microns S.M.D. The optimum spray cone angle is more difficult to define, and, since it will affect the flame shape, at least in the higher S.M.Ds, it may be expected to vary with the application. In the majority of cases, a long flame is required, and a comparatively narrow cone angle is therefore employed (e.g. 60 deg.—80 deg. included).

With boilers employing combustors on the other hand, it is possible to read across much more from aero gas turbine practice. From the work quoted in section 3 on the burning times of droplets, it will be seen that an S.M.D. of 100 microns with kerosene is equivalent to an S.M.D. of 40-50 microns with residual fuel oil. Other workers have also found that small S.M.Ds of this order are required. Flame radiation should be kept to a minimum to avoid overheating of the flame tube, which means that the residual carbon must be burned rapidly. This further enhances the argument for a fine droplet size. In combustors, of course, the spray angle required is determined by the usual relationship of the spray to the primary flow pattern as described below, and as a result the best angle is usually of the order of 85 deg.-90 deg.

When dealing with heavy fuel oil, some degree of preheating is necessary to enable it to be pumped up to the sprayer without encountering high pipe pressure losses. However, where concern is to maintain a critical quality of spray, the temperature of the oil has to be controlled accurately as the viscosity varies with temperature. Fig. 1 illustrates this point, and also shows that different oils will need different degrees of preheat for constant atomizing conditions. Increasing the degree of preheat will enable the pressure level to be reduced while maintaining the same quality of spray, subject to certain physical limitations, namely air and vapour release, cracking and water release.

Of these factors, probably the most important is water release. Heavy oils contain up to 1 per cent of water, and it would seem most desirable to prevent this from being turned into steam in the pipe lines with the possibility of vapour locks. The higher the pumping pressure, the greater the degree of preheat which can be applied before this happens. Alternatively, the steam may be released with deleterious results in the swirl chamber of a pressure atomizer, due to the pressure drop across the tangential inlet slots. Preheat temperatures of 127 deg. C. (260 deg. F.) are in common usage, but there seems to be no good reason why this should not be considerably increased, particularly if steps are taken to minimize the water content of the oil.

On grounds of simplicity the swirl atomizer is the obvious choice, but on the other hand, due to the high fuel pressures employed (150lb. per sq. in.-1,000lb. per sq. in.), the metering orifices in the atomizer are relatively small. Furthermore, for a flow number of say 10, the finest atomization obtainable will be an S.M.D. of not much better than about 100 microns at the maximum pressure quoted. This would not appear to be fine enough for the burning of heavy fuels in combustors, for the reasons given above.

With a simplex atomizer as described above, the flow turn down ratio is limited to about 2/1 in practice due to the fact that this type of atomizer obeys a square law relationship

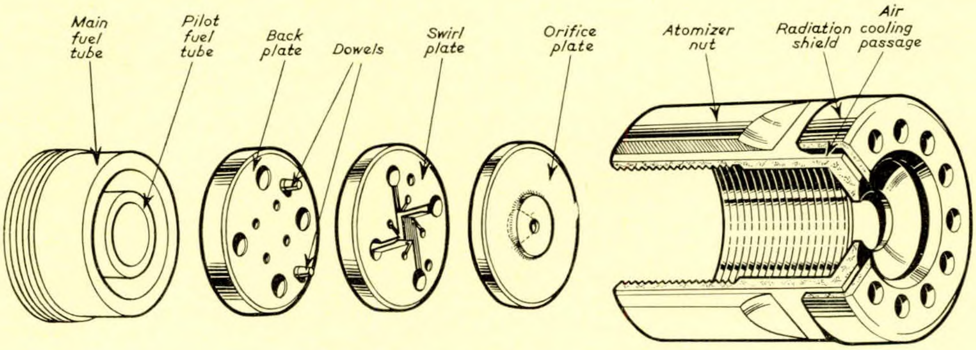


FIG. 12—*Duplex I atomizer (exploded view)*

between the flow and atomizing pressure. The atomizer shown in Fig. 4 is available in a flow number range from 0·2 to 1·4, while that shown in Fig. 5 covers a flow range of 200lb. per hr. to 2,700lb. per hr. at atomizing pressures up to 550lb. per sq. in., equivalent to a flow number range of from about 1 to 14.

Wider flow ranges can be covered with a satisfactory degree of atomization by two-passage atomizers in which the passages both carry positive fuel flows (duplex) or one feed and one return (spill).

Fig. 12 shows an exploded view of a duplex atomizer of the common swirl chamber type in which a single swirl chamber is fed alternatively from pilot slots or main slots or partly from each. The maximum flow rating for this type varies from 2,200lb. per hr. at 550lb. per sq. in. atomizing pressure to 5,500lb. per hr. at 850lb. per sq. in. (combined flow). Minimum flow (pilot only) varies from 300lb. per hr. to 550lb. per hr., and turn-down ratios of better than 5 : 1 are readily obtainable. Fuel up to a viscosity of 3,500 seconds Redwood No. I at 100 deg. F. or even more can be handled provided it is preheated before atomization to a temperature at which its viscosity is 15 c.s.

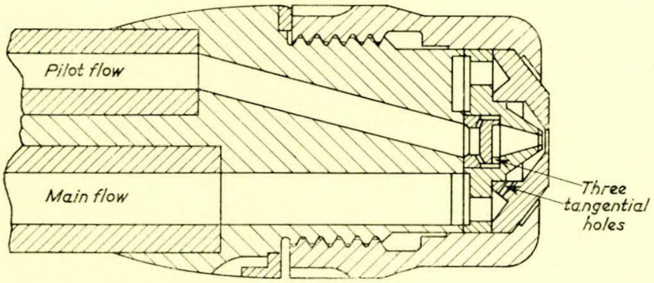


FIG. 13—*Duplex III atomizer (diagrammatic cross section)*

Fig. 13 shows an improved form of duplex atomizer (duplex III) in which the two concentric sprays are entirely separate, and in which, as a result, the cone angle of the spray is independent of the ratio of "pilot" and "main" flows.

The single swirl chamber duplex I type is known to be very inefficient at low flows, and as this is partly due to viscous losses, this type is not very suitable for heavy oil applications where a turn down of more than about 2 : 1 is required. Though there is little experience of operating the coaxial swirl chamber duplex III type on these fuels, there is no reason why turn-down ratios of 5 : 1 and better should not be obtainable.

Fig. 14 shows the components of a spill type sprayer in which the fuel is introduced to the swirl chamber *via* four tangential slots and the spilled fraction leaves the swirl chamber by specially shaped apertures in the back face.

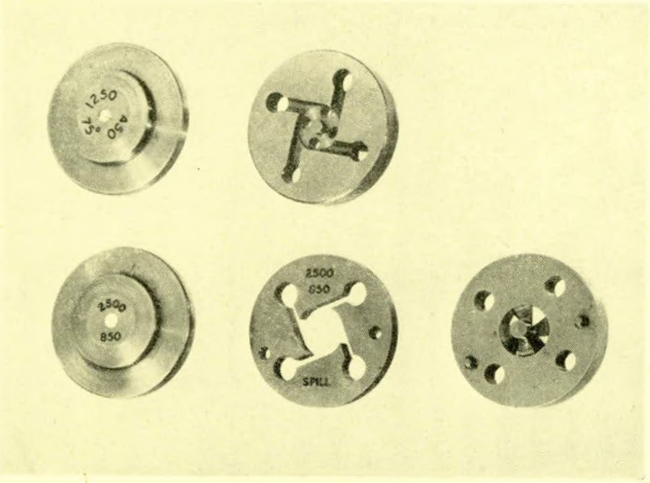


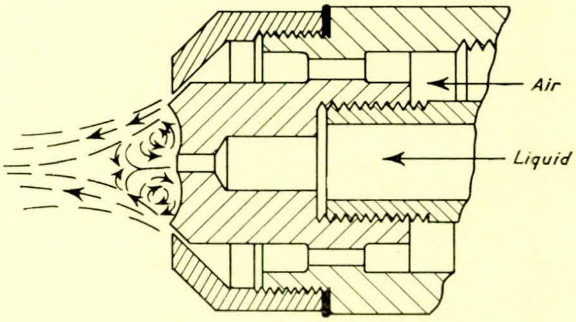
FIG. 14—*Components of spill type atomizer*

The advantage of the spill sprayer is that it avoids the very small passages of the duplex type and that a turn-down ratio of 15 : 1 or better is readily achieved. Experience with this type indicates that the droplet size should stay almost constant provided the input pressure is held constant. The provision of a spill line is not a disadvantage since a recirculatory circuit has to be provided even with the simplex or duplex type in order to maintain the preheat conditions when running at low flows.

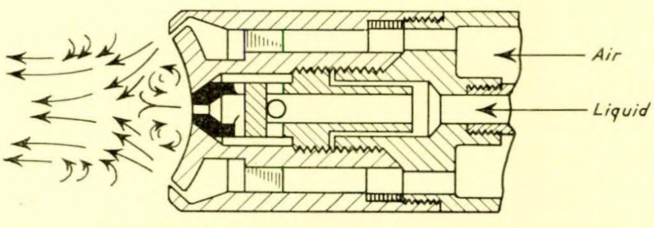
The spill sprayer shown in Fig. 14 uses a fixed fuel input pressure of 850lb. per sq. in., and the range of maximum flows obtainable with the different sizes is from 2,500 to 3,750lb. per hr. Turn-down ratios of from 10 : 1 to 20 : 1 are available, and even 25 : 1 can be obtained in certain cases without exceeding a cone angle of about 120 degrees.

The greatest disadvantage of the spill type is that the spray cone angle alters with output so that in the case of the register, the flame shape may vary and the boiler efficiency may suffer, while in the case of the combustor the correct relation of the spray to the primary vortex cannot be maintained at all conditions. The same wide operating range could be obtained by using a series of simplex atomizers and changing over throughout the range. There is little doubt that this would give a maximum operating efficiency at some expense in convenience. Therefore in some cases the spill system is to be preferred on grounds of flexibility.

A substantial reduction of S.M.D. can be achieved by the use of air as an atomizing agent. Fraser(10) has shown that the best atomizing effect is obtained by allowing the air and fuel to impinge at right angles. Fig. 15 shows a particular arrangement he has evolved for bringing this about by aerodynamic means outside the discharge orifice. In the upper sketch, the fuel is emitted as a pencil jet, and in the lower, as a conical spray.



SIMPLE VORTEX CUP



SWIRL NOZZLE COMBINED WITH VORTEX CUP

FIG. 15—*Principle of air atomization*

Utilization of the available air pressure drop across the combustion system for this purpose will in general only produce a marginal improvement since this pressure drop is so small, but if a separate supply of air at a pressure of, say, 15lb. per sq. in. gauge is made available for the purpose of atomization, the result is an atomization system of an inherently flexible type. Not only could the droplet size be adjusted to almost any value at all flows, but also the flame shape could be expected to be readily adjustable in the case of registers. Metering orifices are relatively large as the metering can be done at low pressure drops. This provides the only method of atomizing small quantities of highly viscous oil, and viscosities of up to 50 centistokes at the orifice can be handled. Remembering the small droplet size which would appear to be necessary from the above arguments (i.e. about 40 microns S.M.D.) this would appear to be the only means of providing it for the purpose of burning heavy residuals.

Though steam is a possible alternative to air under pressure as an atomizing agent, it may interfere with the kinetics of the combustion reaction.

3. EVAPORATION AND BURNING TIMES

As pointed out above, the evaporation of the droplets is a necessary prerequisite to their combustion. Spalding(4) has evolved a general method for calculating simultaneous heat and mass transfer across a phase boundary, depending upon the fact that the fundamental differential equation and the boundary condition equations for the heat transfer can be thrown into the same form as the corresponding equations for mass transfer.

The approach of most other workers has been more empirical. In the cases studied in the present paper, evaporation takes place into an atmosphere which is much hotter than the droplet itself and the position is further complicated by variations of the velocity of the droplet relative to the atmosphere. Frössling(1) and others have evolved equations dealing with the case of comparatively low relative velocities, while Spalding and others have dealt with the high velocity case. A review of all these data has led to the following empirical expression for the mass rate of evaporation (gm/sec.): —

$$10^{-6} K \pi d \Delta T \ (1 + 0{\cdot}6\ R_e^{0{\cdot}5})$$

where ΔT = temperature difference between fuel and atmosphere (deg. C.)

K = $1{\cdot}36 - 0{\cdot}002M$ (for fuels having $M > 130$)

d = droplet diameter, cm.

R_e = Reynolds number

M = molecular weight of fuel

The above equation only holds so long as pyrolysis does not occur and it is therefore of general applicability to distillate fuels which may be defined for this purpose as those which, at a pressure of one atmosphere, are completely vaporized below 350 deg. C. (662 deg. F.).

If any droplet assumes a temperature above 350 deg. C., it is very likely that pyrolysis will occur to some extent. The kinetics of pyrolysis do not concern us here except where the process results in the production of carbon, and since carbon formation is so dependent upon temperature, the measurement of temperature gradients within burning drops is of great interest. Hall(11) has found a maximum temperature increase of some 200 deg. C. (392 deg. F.) for a burning droplet of tetralin of initial diameter 1 mm. and initial temperature 20 deg. C. (68 deg. F.). He concludes that convection and other currents arise fairly readily in large droplets but that they are much less likely to occur with small droplets. It is interesting to note that about half the heat received by the drop is devoted to evaporation and half to rise of droplet temperature until appreciably more than half the mass of the drop has been burnt. Hall's work largely confirms the heat transfer predictions of Hottel and others(5).

It will therefore be obvious that high boiling point fuels may well suffer a fair degree of pyrolysis before combustion is complete. Reliable data are scarce, but the following life history may be postulated: —

1. The majority of the vapour is evolved before solidification occurs.
2. The less volatile matter is then polymerized to a pitch-like material.
3. By the time 80 per cent of the volatile material has been removed, the remaining particle will be virtually solid and in the form of a black spheroid, or ceno-

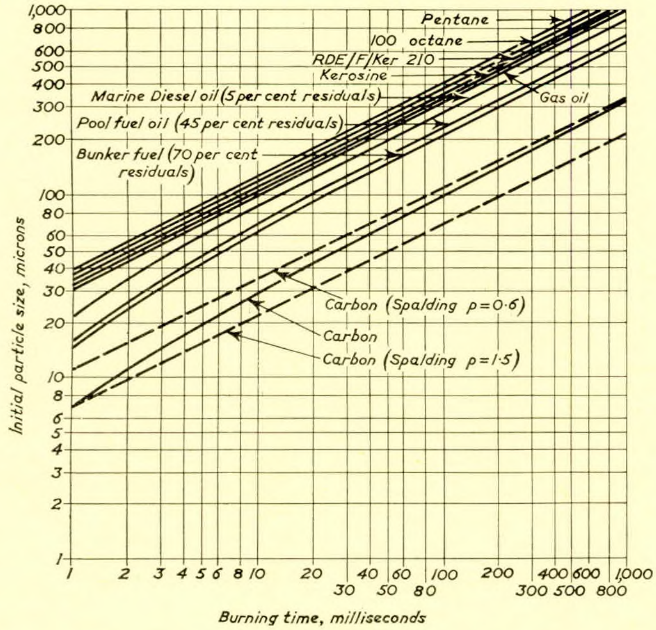


FIG. 16—*Burning times of fuel droplets, zero relative velocity*

Conditions:

Relative air velocity ...	0ft. per sec.
Inlet temperature ...	300 deg. K
Boiling point of fuel ...	Tb deg. K
Air temperature... ...	2,300 deg. K
ΔT	(2,300-Tb) deg. K
Pressure...	1 atm.

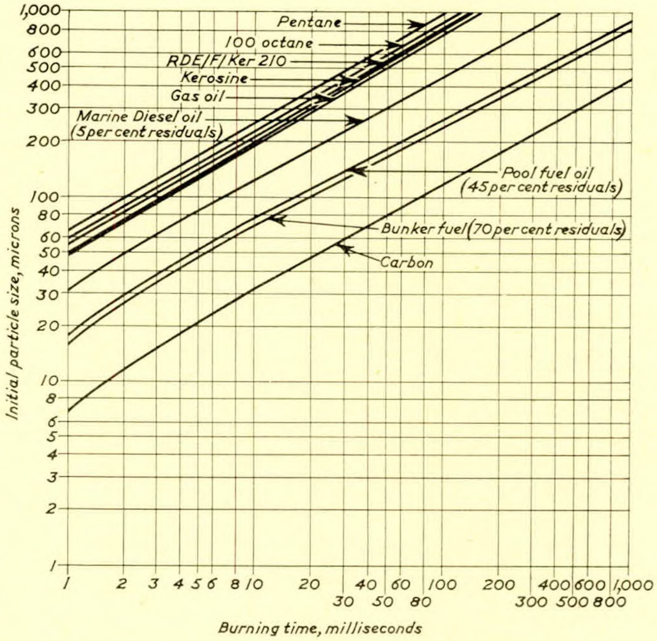


FIG. 17—*Burning times of fuel droplets, 250ft. per sec. relative velocity*

Conditions:

Relative air velocity ...	250ft. per sec.
Inlet temperature ...	300 deg. K
Boiling point of fuel ...	Tb deg. K
Air temperature... ...	2,300 deg. K
ΔT	(2,300-Tb) deg. K
Pressure...	1 atm.

sphere, some 60 per cent of the original diameter of the droplet.

4. Further evaporation continues until the particle is some 50 per cent of its original diameter and about 10 per cent of its original weight.
5. Combustion of the carbon cenosphere will then occur.

Assuming that evaporation and burning of the carbon cenosphere is the controlling feature of droplet combustion, Figs. 16 and 17 illustrate typical combustion times for various fuels at zero and 250ft. per sec. velocity relative to the atmosphere. For comparison, the burning time of a carbon particle as predicted by Spalding has been included.

Extension of data on single droplets to sprays may be difficult due to the droplet spectrum. In addition, droplet distortion, unsteady-state evaporation or droplet interaction may occur.

Probert(3) assumes that all the droplets have zero velocity relative to the air and that the spray distribution follows the Rosin-Rammler law. Using an evaporation equation similar to that quoted above, he calculates the fraction of the spray remaining unevaporated after a given period of time. The analysis was not, at the time, confirmed experimentally, but recent work has indicated that the centre drop of a simple, three-dimensional, body centred, cubic array of nine droplets burning in air has evaporation characteristics similar to those given by Probert; i.e. that the square of the droplet diameter decreases linearly with time.

4. CARBON DEPOSITION

Brief reference has already been made in sections 2 and 3 to some factors affecting the tendency to the formation of carbon deposits in combustion chambers. This tendency may arise from physical or chemical causes, or from a combination of both. The fuel composition, the air/fuel ratio distribution in the chamber, and local design features all exert their influence.

Fundamental investigations on these effects have been carried out in the Company's laboratories using test combustion chambers specially designed for the purpose. These chambers were provided with special facilities for independent control of the primary and secondary air flows, and with arrangements for control of the primary flame tube temperature by adjustable air cooling. Tests were also conducted on the effect of droplet size.

It is well known that overrichness of the fuel/air mixture tends to favour carbon formation, and there is a steep increase in carbon formation rate for mixtures richer than stoichiometric.

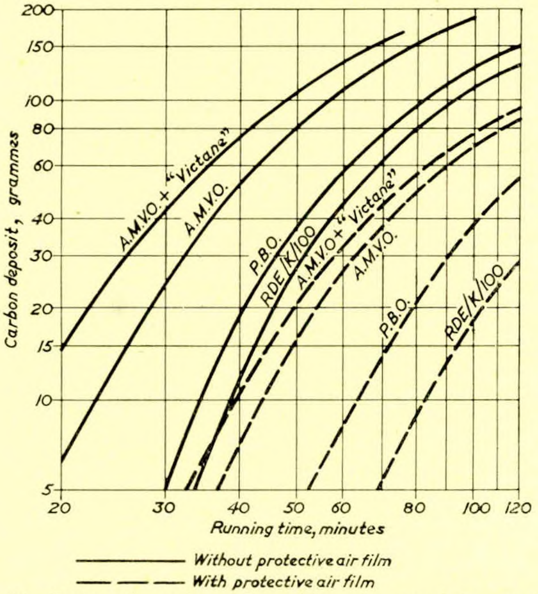


FIG. 18—*Rate of carbon deposition in special experimental combination chamber showing dependence on fuel composition and protective air film*

There are reasons to expect that fuels of high carbon/hydrogen ratio or those containing unsaturated compounds, aromatics or olefines, would form carbon more readily, and Fig. 18 shows the experimental verification of this effect. Weight of carbon deposit is plotted as a function of time for four different fuels, whose aromatic and olefine content and carbon/hydrogen ratio are given in Table II. It will be seen from the figure that increase of aromatic content is consistently associated with an increased rate of carbon build-up. The amount of carbon deposited in the particular chamber used as a test vehicle tends to approach a maximum value somewhere between 180 gm. and 200 gm., when apparently the rates of formation and of burning and erosion of the carbon become equal.

TABLE II.—FUELS PROPERTIES RELEVANT TO CARBON FORMING TENDENCY

Fuel	Aromatic and olefine content, per cent	Carbon/hydrogen ratio
100 octane petrol	—	5·65
RDE/K/100, a kerosene from which the aromatics and as much as possible of the sulphur have been removed	0	6·13
Aviation kerosene (P.B.O.)	8·2	5·9—6·15
A.M.V.O., a relatively high aromatic fuel	17·4	6·27
Gas oil	—	6·54
80 per cent A.M.V.O. + 20 per cent "Victane" (the latter being a proprietary fuel consisting mainly of tertiary-butyl-benzene)	33·9	6·7
Heavy fuel oil	—	7·55

The table brings out the correlation with carbon/hydrogen ratio as well as aromatic content, and shows the extreme range of carbon/hydrogen ratios from petrol to heavy fuel oil which is therefore associated with a much wider variation of carbon forming properties.

One of the simplest forms of protection against the deposition of carbon in a combustion system is the use of a film of surface scrubbing air. Fig. 18 shows the effect of a film of

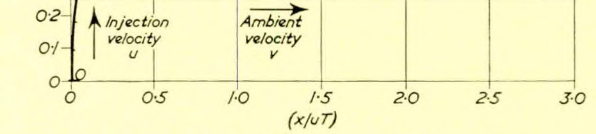


FIG. 19—*Trajectory of carbon particle*

Time constant: $T = 2r^2\rho_c/9\mu$

where r = particle radius

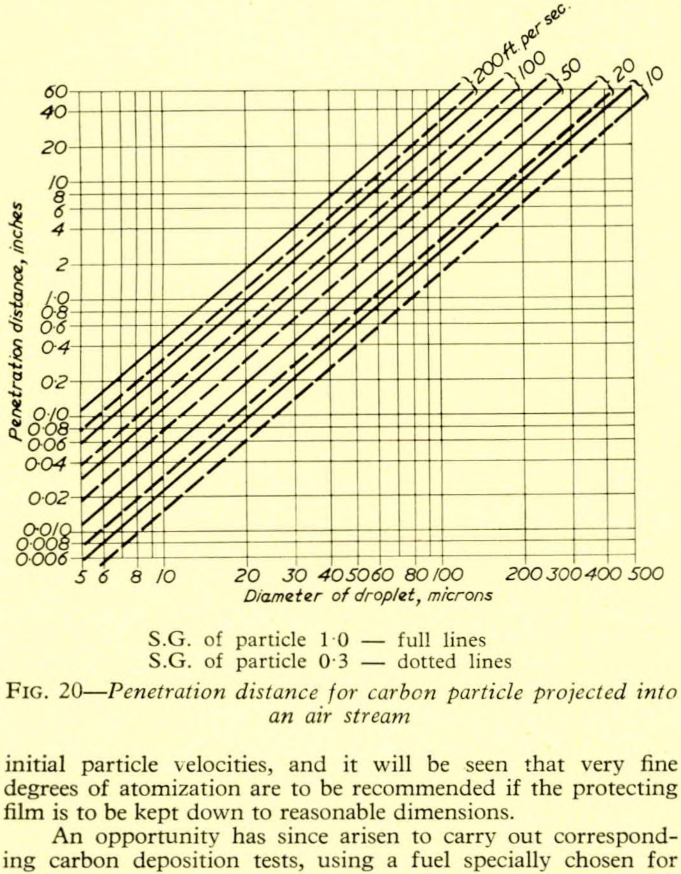
ρ_c = particle density

μ = ambient absolute velocity

scrubbing air in addition to that of aromatic content, since the tests were repeated with two different flame tube arrangements, in one of which the holes feeding the air film were blanked off. It is obvious from the curves that the air film had a very marked effect in delaying the deposition of the carbon.

With regard to the manner in which the film prevents a carbon particle from reaching the surface of the flame tube, it will be noted that for a given initial velocity of the carbon particle perpendicular to the air film, the depth of penetration of the particle into this film will be limited by the phenomenon of viscous drag, as exemplified by Stokes' Law.

The trajectory of such a carbon particle is shown in dimensionless terms in Fig. 19 and it will be seen that, for complete protection of the surface as far as the point at which turbulent effects take over, it is necessary to have a film thickness equal to the product of the initial component of velocity of the carbon particle perpendicular to the film and a certain time constant depending upon the particle size and density and the air viscosity. This dictates a film thickness which is shown plotted against the particle size in Fig. 20 for a variety of initial particle velocities, and it will be seen that very fine degrees of atomization are to be recommended if the protecting film is to be kept down to reasonable dimensions.



S.G. of particle 1·0 — full lines
S.G. of particle 0·3 — dotted lines

FIG. 20—*Penetration distance for carbon particle projected into an air stream*

An opportunity has since arisen to carry out corresponding carbon deposition tests, using a fuel specially chosen for its high calorific value on a volume basis. Associated with this property, there was a very high unsaturated content, namely 64 per cent combined aromatics and olefines, which, with a bromine number of over 8, implied a true aromatic content of some 56 per cent. In these tests the smoke formation was measured as well as the actual carbon deposition. A representative variety of combustion chambers was tested, and all showed considerable smoke formation even at the full load condition where kerosene would give smoke free operation.

In a still later series of tests, fuels with aromatic contents up to 90 per cent by volume were examined. The results confirmed that the aromatic content appears to be a controlling factor for carbon deposition.

5. AERODYNAMIC REQUIREMENTS OF FLAME STABILIZATION

If the velocity of a gas mixture exceeds the local flame speed, whether laminar or turbulent, the flame will be unstable. If, however, an attempt is made to achieve stability by lowering the air velocity sufficiently far, the consequence in terms of pressure loss will be as shown in the graph of Fig. 21.

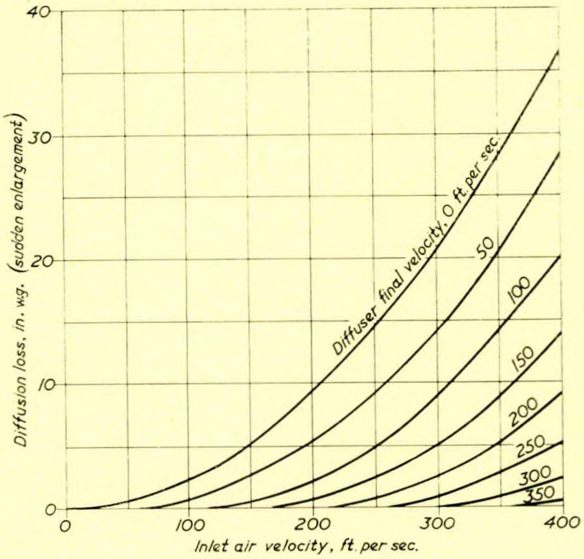


FIG. 21—*Diffuser sudden enlargement loss*

Any considerable reduction of velocity such as is illustrated in this curve is often achieved only at the expense of incurring a pressure loss of the order of the corresponding sudden enlargement loss shown. This loss would, of course, be in addition to the flame tube wall loss, or combustion loss proper, as described in section 8.

For this reason, and also because the use of extremely low air velocities would lead to excessively bulky equipment, it is necessary to provide a flame stabilizing baffle. This provides a flame piloting effect and makes it unnecessary to reduce the mixture velocity below the flame speed except in a very small region close to the fuel injector.

The design of a suitable baffle is described in section 6.

6. FLOW PATTERN DEVELOPMENT

Starting with the simplest form of flame stabilizer, the transverse flat baffle, with its characteristic unstable, unconfined flow reversal on the downstream side, successive elaborations may be introduced to improve the suitability of the pattern, culminating in the composite pattern shown in Fig. 22, which provides for full stabilization and control of the reversal and also a controlled proportion of fresh air to products of combustion recirculating in it. The details of the approach flow pattern shown would vary from case to case, of course, according to the nature of the approach ducting.

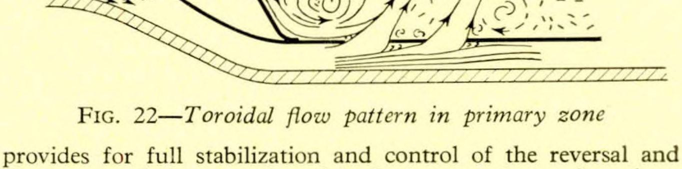


FIG. 22—*Toroidal flow pattern in primary zone*

The development of the toroidal vortex flow pattern and

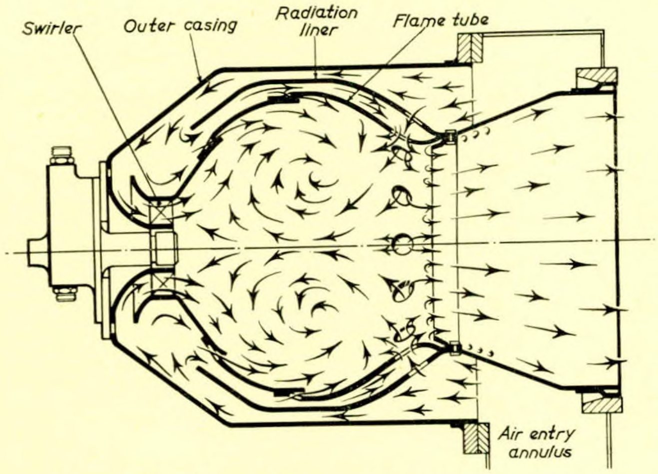


FIG. 23—*Flow pattern in air cooled combustor*

the combustion studies associated with it were undertaken in connexion with the development of the aero gas turbine during and after the last world war. Since this time, various branches of industry have seen the possibilities of applying this system to industrial burning requirements. The fully turbulent, high heat release system was accordingly embodied into a combustion chamber, known for these applications as a combustor, as stated in the introduction.

Due to the special considerations of increased carbon forming propensities and increased heat transfer by radiation in certain cases, it is necessary to depart from the usual cylindrical flame tube shape and adopt a convergent divergent shape as shown in Fig. 23. The actual application is of the reverse flow type in which the inlet and outlet are both at the same end of the chamber.

The overheating problem has been tackled by the introduction of films of skin cooling air at sufficiently frequent intervals from the primary swirler onwards.

The degree of throughput and turn-down which can be obtained from a given flame tube depends to a large extent on the primary zone air flow pattern. This pattern has been investigated by means of the now well known hydraulic analogy method using a perspex model.

Fig. 23 also shows the flow pattern as determined by this method, and it will be seen that the toroidal vortex pattern is achieved by injecting the main streams of primary air through the convergent portion of the wall of the primary flame tube. The pressure loss involved in doing this is somewhat reduced by allowing part of this air to pass directly through the intermediate liner, but it is necessary to allow some substantial portion of this primary air to approach the flame tube holes *via* the annulus between the flame tube and this liner from the direction of the flame tube head, for the purpose of ensuring an adequate degree of flame tube cooling by external convection. Accordingly, a balance must be struck between these two requirements.

The stability and symmetry of the vortex pattern suggest that an ideal design of flame tube has been attained in this instance. The rate of entrainment of the main jets, as assessed from observations, compares favourably with conventional chambers.

The feature which distinguishes a register from a combustor is that there is no lateral or longitudinal control of the flame generated by a register. This system therefore becomes important when it is desirable for the flame to be within a boiler in order to achieve the optimum conditions of heat transfer to the water tubes or to the fire tube as the case may be. In these cases it is still possible, and in fact desirable, to realize the toroidal vortex pattern downstream of the register itself, and this can be done by suitably directing the air passages.

A simple method of forming a flame stabilizing zone in the case of a register is by means of an isolated swirler as shown in Fig. 24. This figure shows the flow pattern in the approach ducting from the header and also indicates the way in which the quarl confines the flame boundary in the early stages.

The flame piloting zone produced by this means is of rather a different type from that illustrated in the combustor flow pattern in Fig. 23, and is not of the optimum type.

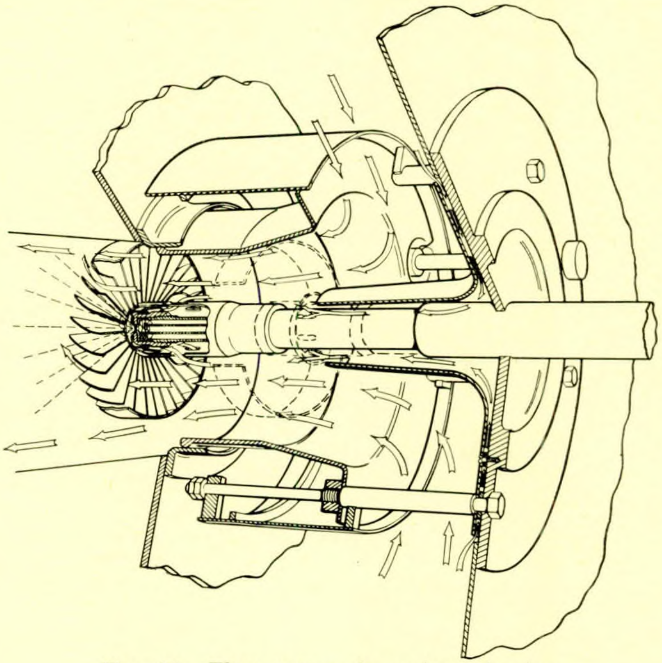


FIG. 24—*Flow pattern in register ducting*

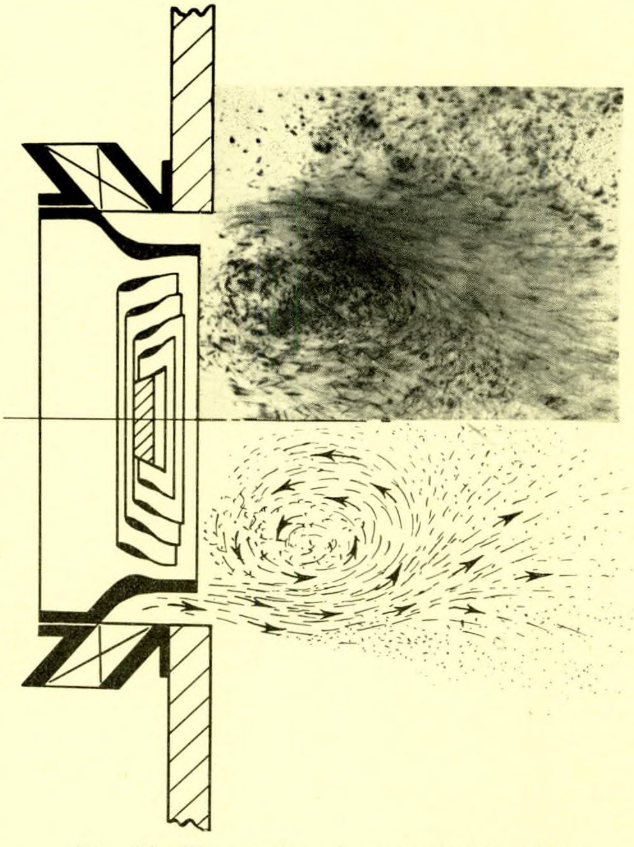


FIG. 25—*Flow pattern downstream of register*

A great deal of work was therefore done on scale models of a variety of possible designs, and the best configuration was found to be one in which the sprayer is surrounded by a series of overlapping cones between which a number of coaxial conical sheets of air are admitted, forming quite a vigorous toroidal reversal. Immediately outboard of this assembly, the remainder of the combustion air is admitted through an annular gap with a swirling motion.

In the course of development, it was found that the dimensions and activity of the vortex were sensitive to the angle at which the trailing edges of the conical baffle segments are set. If these angles are too wide, the flow pattern opens out to cover a wider area and at the same time the axial reverse flow feature, so necessary for flame piloting, is lost. If, on the other hand, the angles are too narrow, the toroidal vortex, although still present, is so constricted that its volume is inadequate to perform the flame piloting duty. The optimum pattern and configuration were found by making use of an advanced flow visualization technique in which air bubbles were used as the tracer in a medium of flowing water in a perspex model.

Fig. 25 shows the optimum configuration. Above the centre line will be seen a negative of the appearance of the air bubbles on the visualization rig, and below the centre line the diagrammatic form of the flow pattern as deduced from the observations. Corresponding flow visualization studies revealed that the register arrangement incorporating swirlers only, and no flat or conical baffles, although capable in some instances of producing reverse flow regions for flame stabilization, gave a pattern subject to a great deal of unsteady flow with random vortex formation.

The use of a controlled toroidal recirculation of the type described above for the purpose of flame stabilization is known as the "stabilized flame" principle, and this principle is used in all combustor and register equipment manufactured by the authors' Company for industrial applications.

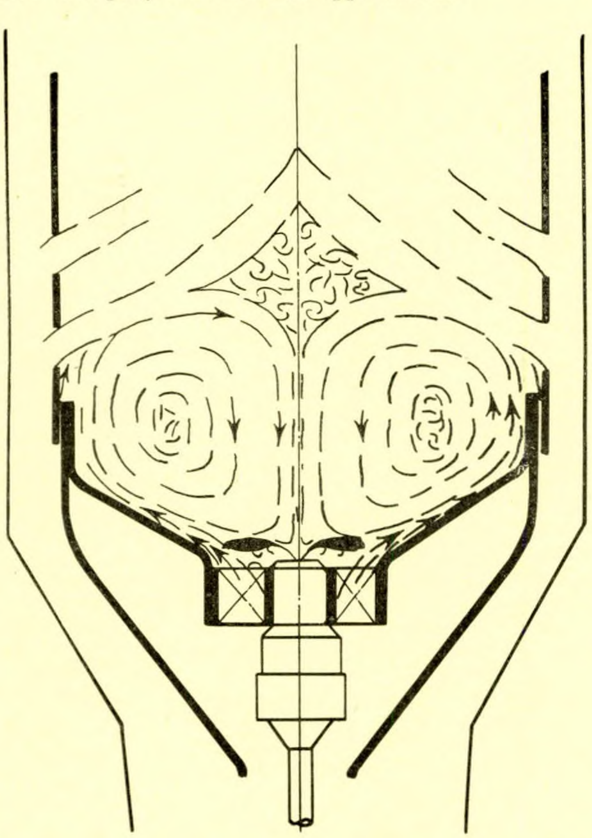


FIG. 26—*Relation between spray and air flow pattern (low fuel flow)*

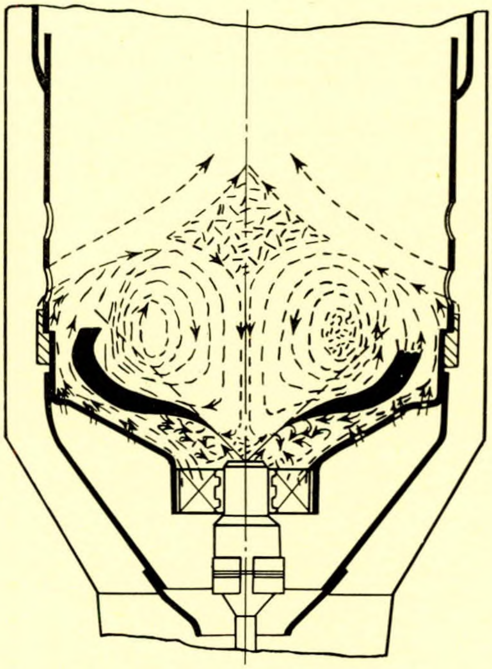


FIG. 27—*Relation between spray and air flow pattern (high fuel flow)*

7. RELATION OF THE FUEL SPRAY TO THE FLOW PATTERN

The relationship of the spray to the primary air vortex can be approached theoretically or from the point of view of practical experimentation. By means of the hydraulic analogy rig mentioned elsewhere, it may be shown that at small fuel flows, the path of the fuel is greatly influenced by the air flow pattern, while as the fuel flow increases progressively, this influence is delayed to a later and later stage.

Figs. 26 and 27 show small and large fuel flows in a downstream injection combustion chamber. For low fuel inputs, the influence of the fuel spray on the flow pattern will be very local, and will be confined to the vicinity of the atomizer orifice with no influence on the general primary zone flow pattern. The fuel droplets leaving the atomizer will be picked up by the air and swept round the extremities of the torus. The effect of the central upstream flow of air upon a small downstream fuel flow widens the spray cone angle.

For high fuel flows in the downstream case, the influence of the cone of fuel from the atomizer will be sufficient to modify the air flow pattern to such an extent that air which previously flowed from the reversal to join with that from the swirler would be deflected by the fuel cone. This results in a reduction of the size of the torus, as may be seen in Fig. 27.

Turning to the theoretical aspect, it is possible to calculate from the equations of motion and evaporation the path followed by any droplet in a given flow pattern. Fig. 28 shows

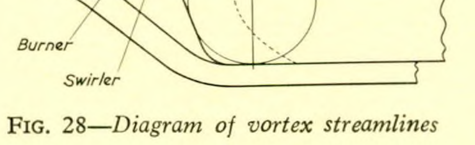


FIG. 28—*Diagram of vortex streamlines*

the idealized vortex which has been assumed for calculations of this type in a particular case. This vortex is based on a given velocity profile across the primary zone obtained as a result of actual tests which show that, typically, this velocity follows a fourth power law as illustrated by the dotted curve on this figure. The equation of continuity demands that the core of this vortex should lie very much closer to the flame tube wall than to the axis, a feature which is borne out also in many practical observations.

Making a simple assumption that the vortex consists of homogeneous products of stoichiometric combustion, the most practical way of calculating the path of the spray is the calculation of the trajectory of each individual droplet of which the spray is composed, as if this were not influenced by the presence of the other droplets. This can be done by a step by step method taking into account the evaporation and the consequent reduction in size of the droplet at every stage, and leading to a specific trajectory for each particular size of droplet, as shown in Fig. 29.

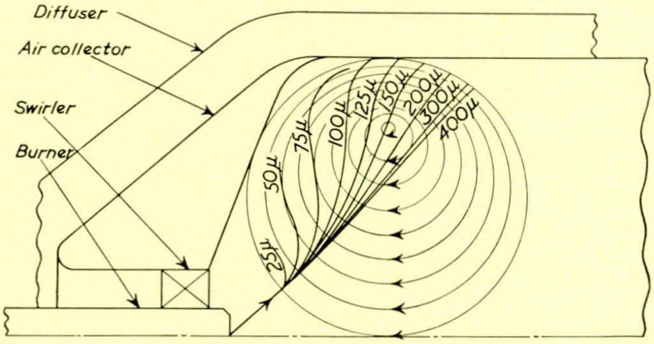


FIG. 29—*Trajectories of droplets of various sizes through the vortex*

A given spray will have a known distribution of droplets in the different size groups and will therefore lie predominantly along one or other of the trajectories shown in the figure, a result which will be seen to be reasonably in agreement with practical observations.

8. HEAT RELEASE RATES

Specific heat release rates are normally expressed as heat flow per unit time, per unit pressure and per unit of either combustion chamber volume or cross sectional area. Table III gives the heat release rates per unit volume for a number of typical combustion processes using a variety of fuels.

TABLE III.—HEAT RELEASE RATES IN TYPICAL COMBUSTION PROCESSES

Fuel	Process	Heat release	Pressure loss, per cent
		B.t.u./ft^3/hr/atm.	$\Delta P/P$
Pool fuel oil	Boiler firing : Induced or natural draught	$0{\cdot}2 \,.\, 10^6$ (maximum)	—
Pool fuel oil	Boiler firing : High forced draught	$1{\cdot}0.10^6$	—
Pool fuel oil	Industrial gas turbine	$1{\cdot}0-1{\cdot}5 \,.\, 10^6$	2·5
Pool gas oil	Industrial gas turbine	$2{\cdot}0-3{\cdot}0 \,.\, 10^6$	2·5
Aviation kerosene	Aero gas turbine	$5{\cdot}0 \,.\, 10^6$ and upwards	4·5 and upwards

The figures in this table are simply typical values chosen to indicate general trends, and it will be seen that the higher heat release rates are generally associated with higher values of pressure loss or draught loss in the combustion chamber, and in fact it may be shown theoretically that this is to be expected. The calculation of primary flow conditions referred to in section 7 gives rise(8) to the following formula for specific heat release: —

$$(786 \,.\, 10^6 \epsilon \eta_r \eta_v \sqrt{T_c}/T_h)\ (\delta/P)^{\frac{1}{2}}$$

where ϵ = excess combustion factor
η_r = vortex refreshment efficiency
η_v = vortex velocity efficiency
T_c = air entry temperature (deg. K)
T_h = vortex gas temperature (deg. K)
δ = flame tube wall pressure loss, lb. per sq. ft.
P = pressure in chamber, lb. per sq. ft. abs.

This formula suggests that the specific heat release will be proportional to the square root of fractional pressure loss, a fact which has been appreciated on an experimental basis for a long time.

9. COMBUSTORS

The combustor has been defined in the introduction, and the basis of its design, centreing around the toroidal vortex, has already been briefly touched upon in section 6.

From the remarks in that section, it will have been realized that the combustor offers the best means of exercising close control over the flame and in fact the whole combustion process. Where the highest possible rates of heat release are required therefore the use of a combustor is to be recommended. This is particularly true of high speed steam generating plant, steam reheaters, etc. The basic type of combustion system represented by the combustor is also the most appropriate type for gas turbine applications, e.g. for power generation.

One of the chief difficulties which is met in the operation of combustors arises in connexion with the burning of heavy fuels, and particularly residuals. The corrosive elements in such fuels are sulphur and vanadium, the latter rendered more destructive by admixture with other compounds which reduce the melting point.

In the gaseous phase, H_2S and SO_2 are the chief offenders, although the former is more likely to be formed under reducing conditions.

Above 250 deg. C. (482 deg. F.), gaseous attack is possible and becomes more severe with rising temperature. Whilst chromium is reasonably resistant to H_2S, nickel and iron are very susceptible to attack. Sulphur dioxide has considerably less action on chromium, nickel and iron, even above 1,000 deg. C. (1,832 deg. F.).

Above 600 deg. C. (1,112 deg. F.) all the heat resisting alloys are subjected to ash attack which becomes severe above 800 deg. C. (1,472 deg. F.).

Of the alloying elements, chromium seems to be the more resistant, but must be present in relatively large proportions (18 per cent upwards). Nickel and cobalt contents do not appear significant in allaying ash attack, although they are better than iron.

Certain alloying elements, notably Mo and V, seem deleterious, but there is some confusion regarding the effects of others such as Ti, Co, Nb and Ta. Silicon appears to be definitely beneficial in resisting ash attack, but imparts other undesirable properties to the alloy. There is some evidence that additions of aluminium can be made advantageously without impairing unduly the high temperature characteristics.

Apart from the possibility of the development of an alloy which will withstand high temperature ash attack, the catastrophic effects of corrosion may be reduced by the following methods, some of which will usually be found to be applicable in any given case:

i. Removal of the offending elements.
    (a) Elimination of such alloying elements as molybdenum and vanadium from heat resisting alloys.
    (b) Removal of vanadium, sulphur, etc., from fuel oil. (In this connexion, the source of supply might be worthy of consideration. Venezuelan

oil, for instance, generally contains much more vanadium than Middle East or Texan.)

ii. By addition of de-activators to the oil. Calcium oxide has been used with some success by injection as a slurry into the oil. A relatively stable and inactive compound $Ca(VO_3)_2$ is formed during combustion. Oxides of Ba, Sr and Mg have also proved beneficial. Sulphur trioxide, however, can react with basic additives to destroy their chemical activity at temperatures below the decomposition temperature of the corresponding sulphate. Thus the effectiveness of magnesium oxide is reduced at temperatures below 700 deg. C. (1,292 deg. F.). Calcium and sodium sulphonates which are soluble in fuel oil have been suggested as possible additives before burning.

iii. By coating the metal surface with a protective layer. Silicon impregnation and phosphate coatings afford some measure of protection, but the adhesion of the latter cannot be assured. Some success has been achieved by chromizing and aluminizing.

iv. An increase in the scrubbing air which is already admitted into the flame tube to minimize carbon deposition could be expected to shield the sheet metal from the corrosive agents.

v. By using an alternative material, e.g. prefired refractory or refractory cement for the parts of the combustor most liable to chemical attack. This presupposes the existence of a refractory possessing sufficient resistance to chemical attack and thermal fatigue and having suitable mechanical properties for the particular installation.

A good example of the way to tackle corrosion problems arising in the course of developing a combustion chamber for a practical application is to be found in a paper(7) on the combustion of residual fuel in the gas turbine fitted to the *Auris* oil tanker.

In the course of the running of this equipment, experiments were carried out by placing test specimens in the ducts before the turbines and examining these at intervals. The major problem studied by the authors is that of ash deposition and its control.

A wide variety of fuel additives were used and the various practical factors involved in their use are discussed at length. The other difficulties with these chambers, namely the combustion and corrosion problems, have been solved to the satisfaction of the users. Finally, a stage was reached when, after 2,400 hours working with heavy oil and additives, there were only powdery layers of deposit on the turbine blades, which never built up.

Fig. 30 shows a photograph of the effect of corrosion on a portion of a combustor of a design similar to that shown in Fig. 23 already described. In this comparative test, two flame tubes had been subjected to periods of running with heavy fuel oil, one of the tubes having been coated with a 0·005-in. thickness of ceramic. The running conditions were 180 hours on 200-sec. fuel oil and 90 hours on 3,500-sec fuel oil.

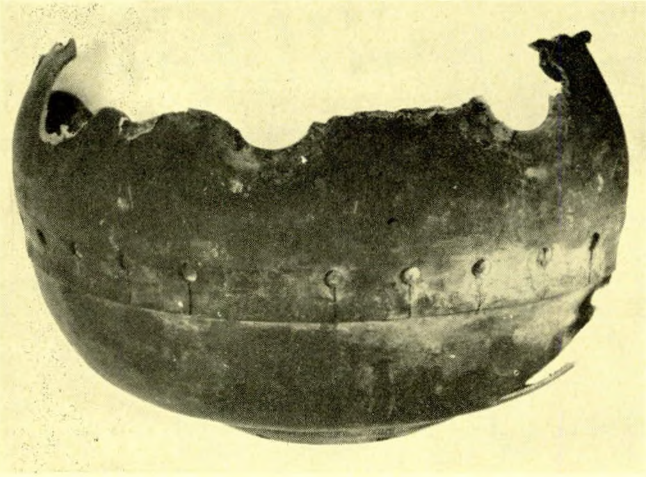


FIG. 30—*Corroded flame tube from a combustor*

The tube shown in Fig. 30 is the one which had not been coated with ceramic. The photograph shows severe corrosion around and between the primary air holes, and this section had in fact almost broken away from the remainder of the flame tube. An area of sulphide inclusions was found at the edge of one of the primary air holes, while in the neighbourhood of the cooling skirt examples were found of both oxidation and sulphur attack.

The tube with the ceramic coating appeared to be in a much better condition than the other. The only severe patch of corrosion was around the cooling skirt. Areas were found on both tubes which showed the effects of grain growth, indicating temperatures in excess of 1,000 deg. C. (1,832 deg. F.), but the degree of sulphur penetration was less in the case of the ceramic coated tube.

This raises the important question of flame tube temperature in a combustor. Adequate consideration of this necessitates a thorough study of the relevant heat transfer processes, i.e. radiation and forced convection, but it is not proposed to make more than a few general remarks on this subject in the present paper.

An important factor affecting the radiation of heat from the flame to the flame tube is the emissivity of the flame. Where the degree of luminosity is not great, it is possible simply to inflate the emissivity factor by an amount determined from experiment. Where, however, residual oil is used, the effect of the carbon particles is very much greater, and the overall emissivity may approach unity.

Under these conditions the heat transfer from the flame to the flame tube may consist of as much as 90 per cent radiation and only 10 per cent convection.

A paper by Tipler(6) also makes a study of the heat transfer problem and emphasizes the importance of the following factors: —

a) Luminosity.
b) Flame temperature.
c) Carbon in the flame.
d) Carbon/hydrogen ratio of the fuel.
e) Molecular weight of the fuel.
f) Turbulence.

In this paper special mention is made of the heat transfer properties of ceramic lined walls and of the louvred construction. Tipler has successfully used louvred gaps as narrow as 0·009in. and he deals with the heat transfer calculations for louvred walls in a fairly detailed way, introducing a factor analogous to the thermal ratio used in heat exchanger calculations. These calculations are of great interest to the combustion engineer, since chilling effects and loss of mixing air are involved.

The combustor whose flow pattern is shown in Fig. 23 is a standard 10½-in. diameter combustor burning 200lb. per hr. at an air boost pressure of 12-in. w.g. Gas oil of viscosity 35 seconds at 100 deg. F. is burned after atomization at 250lb. per sq. in. injection pressure.

10. REGISTERS

The distinction between a combustor and a register is that while the combustor exerts lateral and longitudinal control on the flame, the register does not. Thus the combustor is to be recommended when it is desirable to keep the main flame external to the boiler, and the register when it is desirable for the flame to be within the boiler in order to achieve the optimum conditions of heat transfer to the water tubes or to the fire tube as the case may be.

About ten years ago, the Company's laboratories were first approached in connexion with the design of registers for the firing of watertube boilers. There were in existence at that time quite a large number of proprietary designs of register

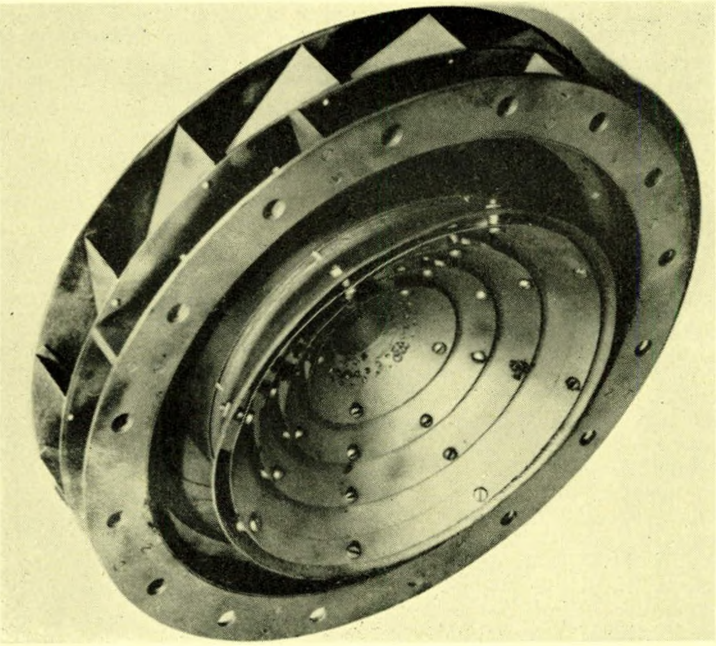


FIG. 31—*Register with fixed overlapping conical baffles*

which apparently fell into three groups as regards the means of providing a flame stabilizing or piloting zone:—

a) The flame hood type in which the fuel injector is situated at the apex of a small conical baffle, or jet shield.
b) The back eddy disc type in which the fuel injector is situated at the centre of a flat baffle.
c) The swirler type in which the fuel injector is surrounded by an air swirler intended to create a local reverse flow region.

It was immediately obvious from a study of these designs that one of the most important fields of study for an improved design would be the flow pattern investigations by means of available flow visualization techniques. At that time, the most convenient of the known flow visualization techniques was the observation of the effect of the air flow in a perspex model upon a small local water jet which could be moved at will throughout the flow region of interest. Even this crude method revealed some valuable points.

The correct Reynolds number of flow was reproduced, and

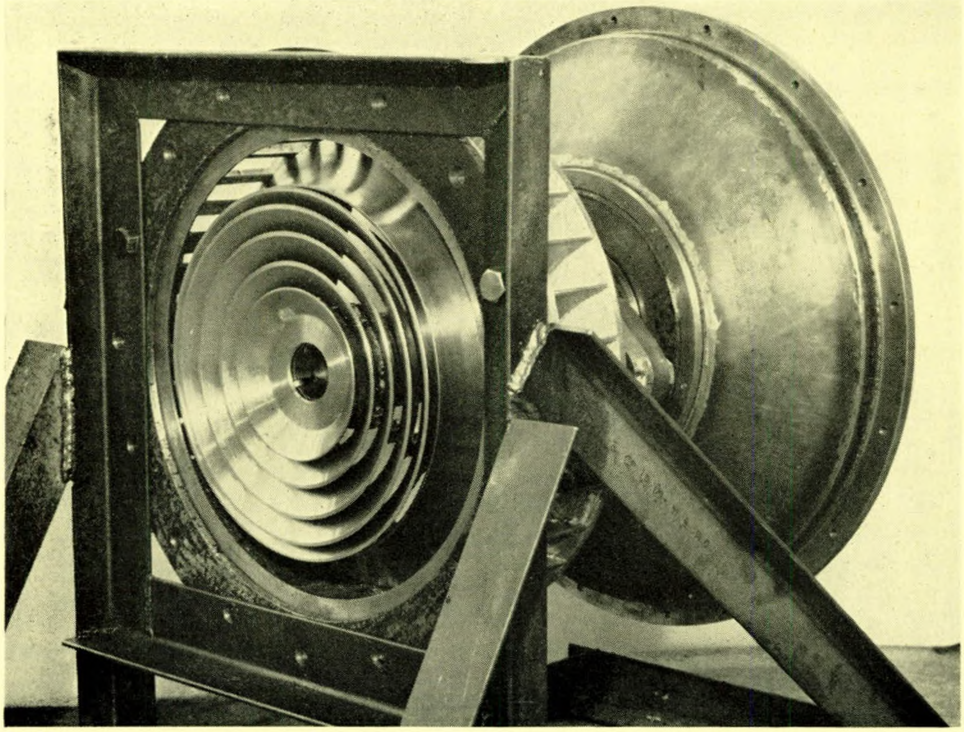


FIG. 32—*Register with movable overlapping conical baffles*

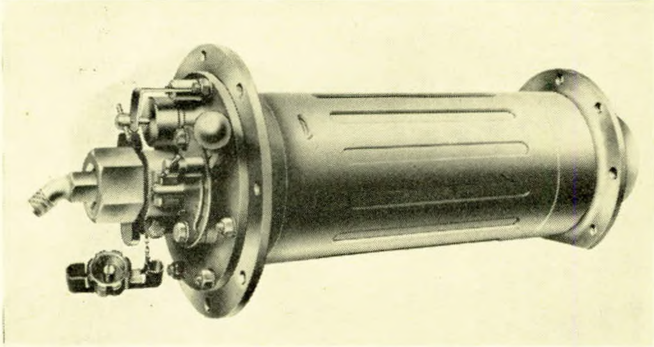


FIG. 33—*6-in. diameter pilot register for marine boiler*

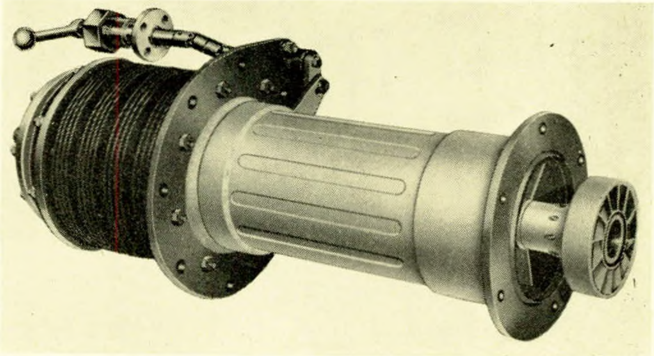


FIG. 34—*6-in. diameter pilot register with bellows adjustment*

it was found that the swirler alone completely failed to produce a reverse flow region. The pattern was much improved by using various sprayer tip cones, but it was found that a true reverse flow region was only produced provided the cone exceeded a certain critical diameter. The flow pattern without any sprayer tip cone was found to be unaffected by the presence or absence of the quarl, but the reverse flow region produced by the tip cone was of smaller axial extent without the quarl.

Referring to the type of flame stabilizer described in section 6 and illustrated in Fig. 25, it was found that, in order to prevent fuel impingement on to the register components or brick throat, a short throat is required, and the normal position of the sprayer should be well forward. The distance from the sprayer tip to the throat discharge section should not exceed half the throat diameter. It was found that the maximum combustion intensity could only be achieved if the sprayer axial position were set within close limits. Fig. 31 shows the configuration arrived at.

Under turn-down conditions, in a register of standard geometrical configuration, all the air flow velocities in the different parts of the system will be reduced in proportion, and in particular, the reversal velocity in the combustion stabilization zone will be reduced. Depending on Reynolds number effects, this reduction may be even greater than the turn-down ratio. This makes for unsatisfactory combustion conditions,

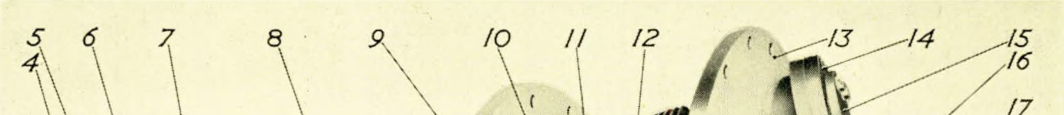


FIG. 35—*Main register for marine boiler (sectional view)*

1) Swirler; 2) Stop nuts; 3) Stop bracket; 4) Atomizer nut; 5) Air scoop; 6) Support rod; 7) Support sleeve; 8) Inner sleeve air guide; 9) Register mounting plate; 10) Support ribs; 11) Observation bellows; 12) Igniter bellows; 13) Screen plate; 14) Igniter flange; 15) Blanking plate; 16) Observation window; 17) "O" ring seal; 18) Burner unit retaining nut; 19) Control handle; 20) Fuel inlet block; 21) Pilot connexion; 22) Main connexion; 23) Seal nut; 24) Seal housing;; 25) Actuator handle; 26) Graphited wiper pad; 27) "Gaco" seal; 28) Actuator locking mechanism; 29) Actuator bellows; 30) Burner bellows; 31) Asbestos sleeve; 32) Burner shaft support tube; 33) Actuator shaft; 34) Support tube; 35) Spring adjusting sleeve; 36) Air slide casing; 37) Pilot fuel tube; 38) Main fuel tube; 39) Fixed air casing; 40) Air casing support flange.

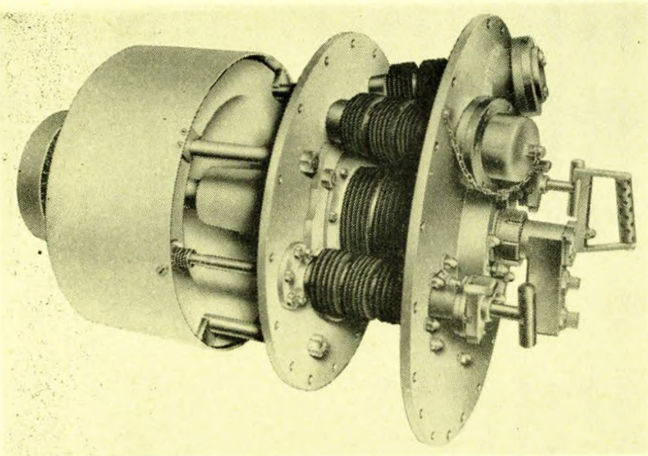


FIG. 36—*Main register for marine boiler (exterior view)*

and in an effort to overcome this registers of variable geometry may be used.

Fig. 32 shows such a register in which the parts of the conical baffle are mounted on pivoted unison bars in such a way that a single movement causes all the conical gaps to varv together. As a result, the air mass flow can be turned down at a constant supply pressure by closing the gaps, while the air injection velocity through these gaps remains constant, and the toroidal vortex remains of undiminished vigour.

Figs. 33 to 36 show applications of registers for marine boilers, all employing the "stabilized flame" principle as described in section 6. Fig. 33 shows an exterior view of a 6-in. diameter pilot register as installed on a marine boiler front, and Fig. 34 shows another example of the same type of equipment, this time with a bellows arrangement to cater for differential thermal expansion. These pilot registers normally burn 200lb. per hr., but can handle up to a maximum of 400lb. per hr. with a draught loss of 1-in. to 24-in. w.g. Fig. 35 shows one of the main registers for the same application. Among other features, the adjustable air casing, double front with bellows connexions, removable duplex sprayer and igniter tube, may be seen. The maximum fuel burning capacity of this register is 2,600-2,800lb. per hr. Fig. 36 shows an overall view of the same register.

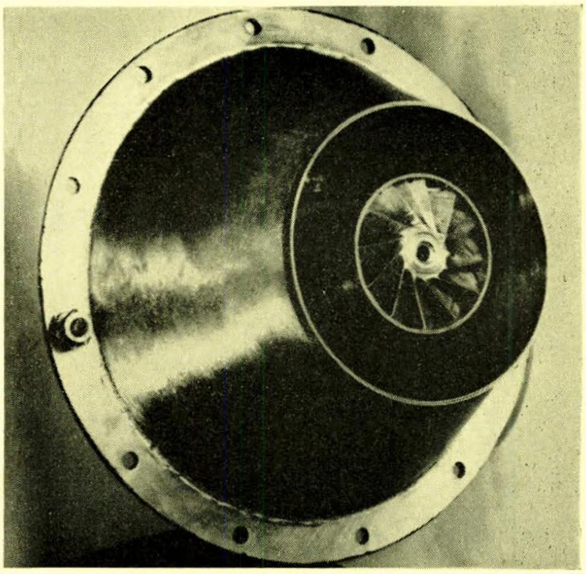


FIG. 38—*Industrial boiler register (rear view)*

From 1953 onwards, air registers have been fitted to the boilers in a number of factories in the authors' Company. The first application of this type was on a La Mont type boiler. Figs. 37 and 38 show front and rear views of this register which will be seen to be of the type having a central swirler surrounded by a feed of secondary air, both air feeds being separately adjustable.

This installation comprised two boilers, each of 11 MBTU/hr. capacity and one of 4 MBTU/hr. The registers burn fuel of 600-1,000 sec. Redwood No. I viscosity at 100 deg. F., which is preheated to arrive at the sprayer at 210 deg. F. Initial trouble with carbon formation on the quarl was due to a local flow reversal near the quarl surface which was cured by admitting a small bleed of air at the appropriate point. The upper limit of burning capacity was 470lb. per hr. for each of the large registers, and at the lower end of the flow requirements, 250lb. per hr. could be burnt satisfactorily at 150lb. per sq. in. atomizing pressure, but for flows below this, smaller atomizers had to be used. The initial perform-

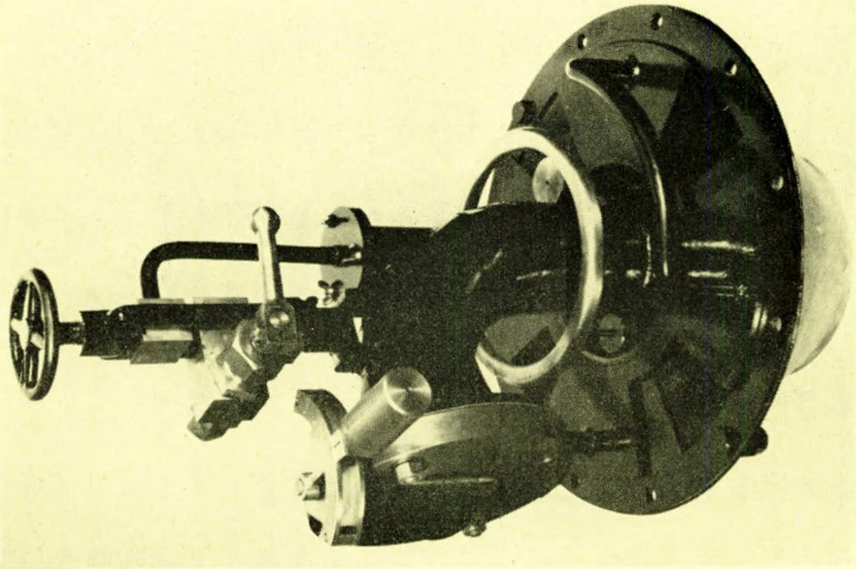


FIG. 37—*Industrial boiler register (front view)*

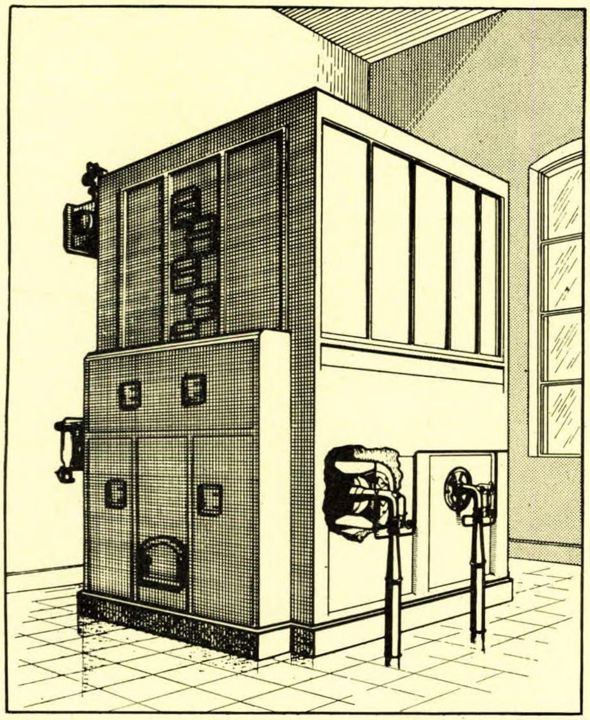


FIG. 39—*Industrial boiler with register in position*

ance of this plant was well in advance of contemporary practice. The boiler gave an exhaust CO_2 figure of some 13·3 per cent at full load when operating with a primary air supply at 6-in. w.g. and a secondary induced draught of 0·52-in. w.g. Fig. 39 shows an overall view of this boiler.

Operating experience with this register revealed a few minor respects in which improvement might be made. Most of these points were related to the finish, and other features of a non-technical nature, the one exception being the forced draught air preheat which was of a very small order since this air simply came through a run of pipe under the boilers. The proposed improvement was to take this air through a heat exchanger incorporated in the flue to obtain preheat to about 150 deg. F.

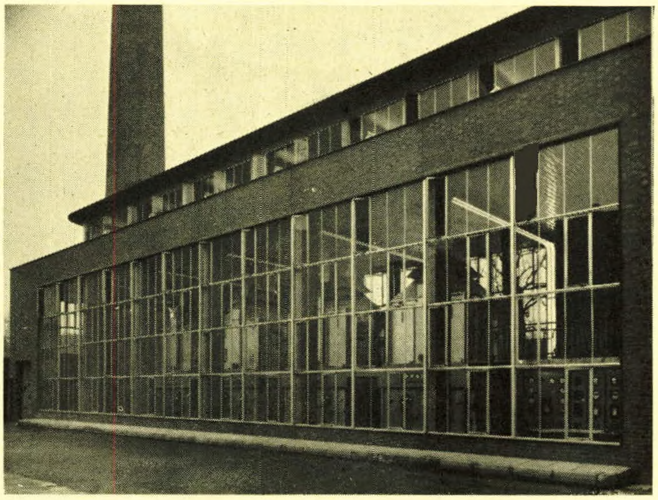


FIG. 41—*Boiler house converted to oil firing (exterior view)*

These features were next incorporated into a register in another factory installation as a trial preparatory to a more major boiler installation which was proposed elsewhere. The register for this trial installation was designed to burn 285lb. per hr. of oil at a mixture strength of 16 : 1. Half of the air flow was injected at a pressure of 6-in. w.g. and the other half induced under the influence of a natural draught of 0·25-in. w.g.

In 1956, the boiler house at the major boiler installation

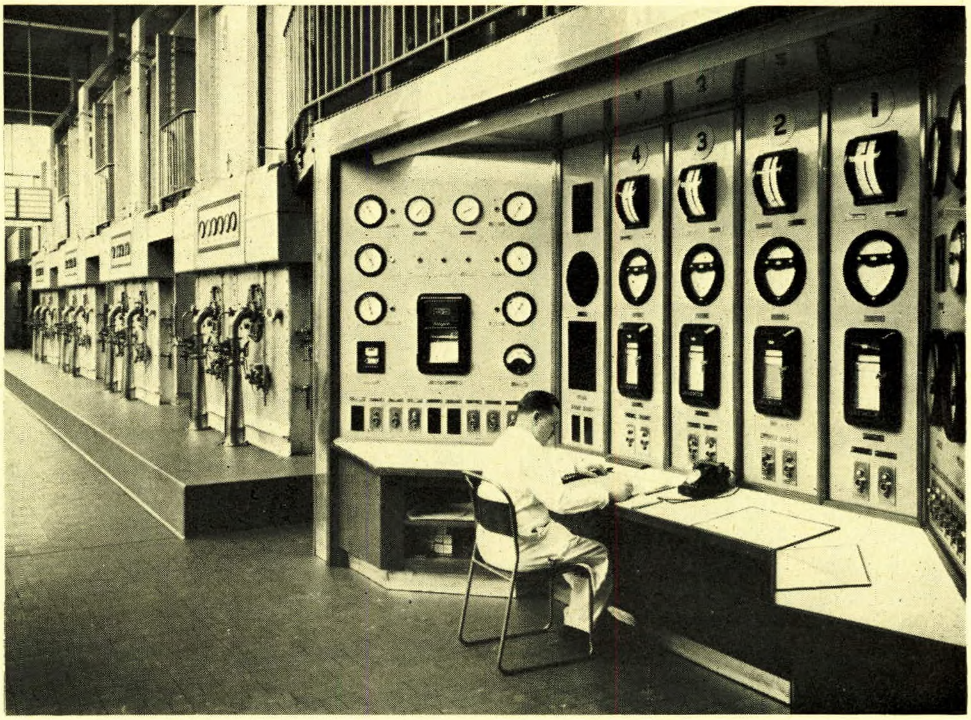


FIG. 40—*Boiler house converted to oil firing (interior view)*

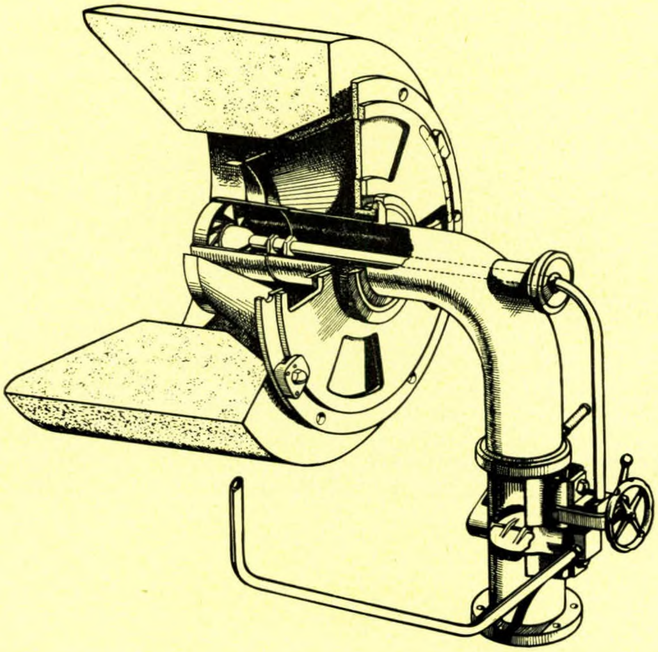


FIG. 42—*Cut away diagram of industrial register*

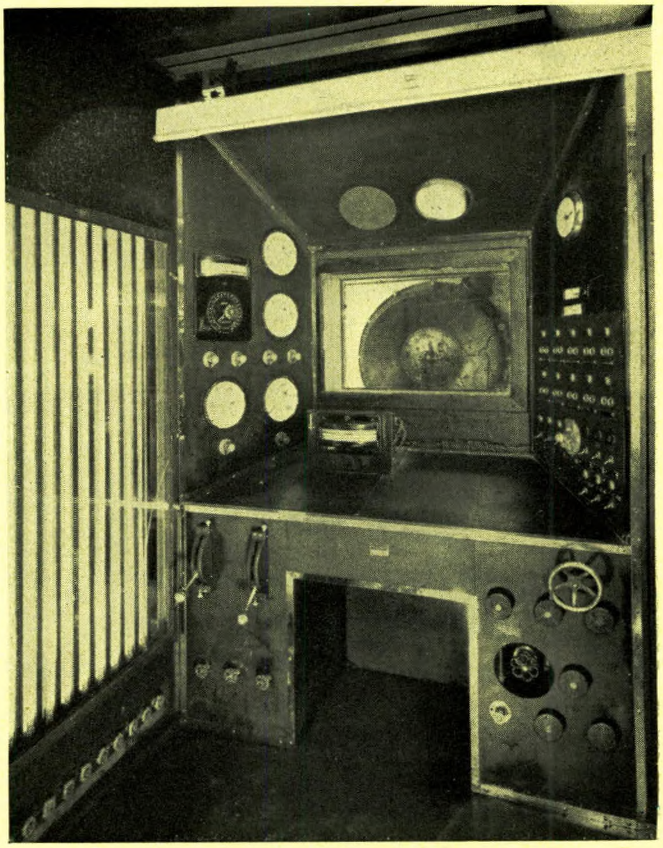


FIG. 44—*Register test facility, control console*

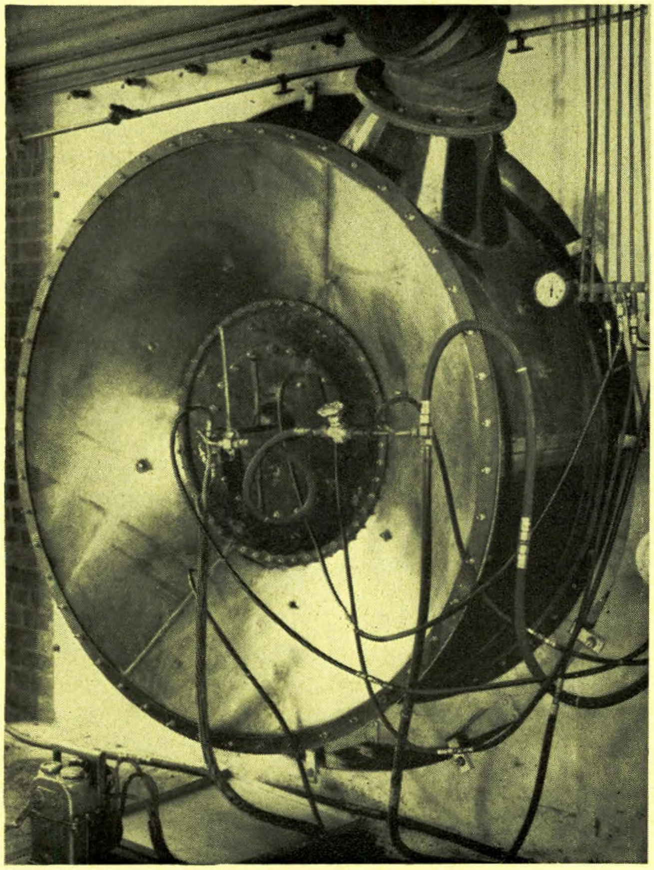


FIG. 43—*Register test facility, universal header*

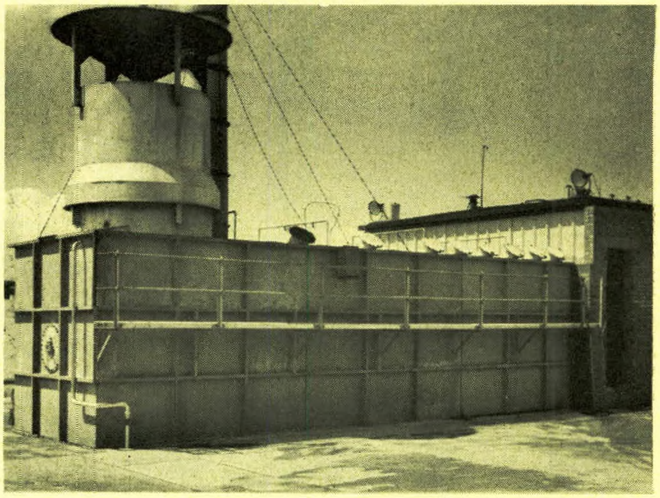


FIG. 45—*Register test facility, silencer and cooler*

referred to above was fully converted to oil firing. There are four boilers each of capacity 10 MBTU/hr. which may be seen in Figs. 40 and 41. These are of the La Mont watertube type in which the water, at a pressure of some 200lb. per sq. in. is heated to a temperature short of the boiling temperature at that pressure. Each of these boilers is fitted with two registers burning heavy residual fuel oil of 950-1,000 seconds Redwood No. I at 100 deg. F. This fuel has a calorific value of 18,600 B.t.u. per lb. and a specific gravity of 0·94 and is heated to some 220 deg. F. before injection, at which temperature it has a viscosity of about 70 seconds Redwood No. I. The fuel flow per register is 37 g.p.h. at a mixture strength of 16 : 1, half the total air flow being up to 650 c.f.m. of primary air at a forced draught pressure of 5·5-in. w.g. and 150 deg. F., and the remainder being induced secondary air at a natural draught pressure of 0·75-in. w.g. Fig. 42 shows a cutaway diagram of the register arrangement. The register plate is spaced away from the boiler front by a gap of about ¼in. to allow for a small flow of scouring air over the surface of the quarl. This installation has now given over two years of very satisfactory service.

For the purpose of research and development testing of register designs, the authors' Company has set up a test facility shown in Figs. 43 to 45. Fig. 43 shows the universal header to which the register on test can be adapted. Registers up to 2,500lb. per hr. can be tested here at present, and the capacity is being increased to 4,500lb. per hr. Air boost pressures available range from 1lb. per sq. in. at maximum flow to 5lb. per sq. in. at lower flows. Fig. 44 shows the control console, the register under test being visible through the safety window. Fig. 45 shows an external view of the silencing and heat removal arrangements for the same register test rig. The products of combustion pass through a 7-ft. diameter discharge tube fully immersed in a water bath.

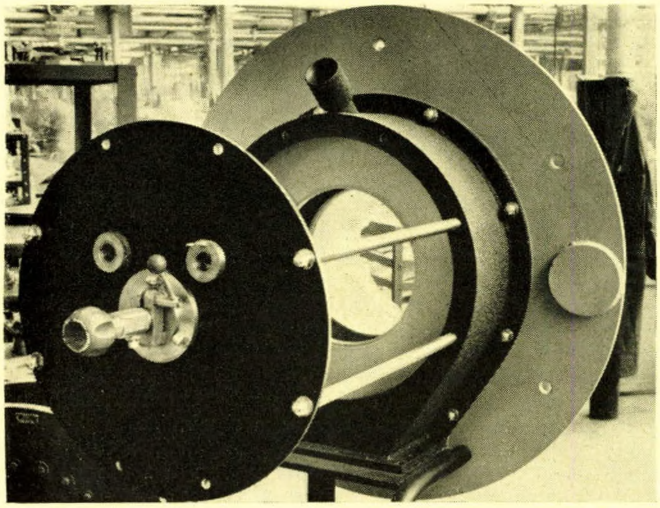


FIG. 46—*"Lancastrian" register (front view)*

The register applications mentioned in the earlier part of the present section are all to watertube boilers, but the register is equally suitable for shell type fire tube boilers, and has in fact been applied to Lancashire boilers of this type at another of their factory installations. Figs. 46 and 47 show front and rear views of the register in question, and several interesting features can be seen. In particular there is the pair of concentric swirlers surrounding the sprayer. These are fed through separate air lines independently controlled, and so forming in effect a duplex air supply system. The maximum forced draught air supply pressure, with both butterfly valves open, is 6-in. w.g. The air and fuel flows are 1·11lb. per sec. and 250lb. per hr. respectively, i.e. an air/fuel ratio of 16 at the full load. At partial loads, the air and fuel flows are reduced in proportion, giving the same constant air/fuel ratio.

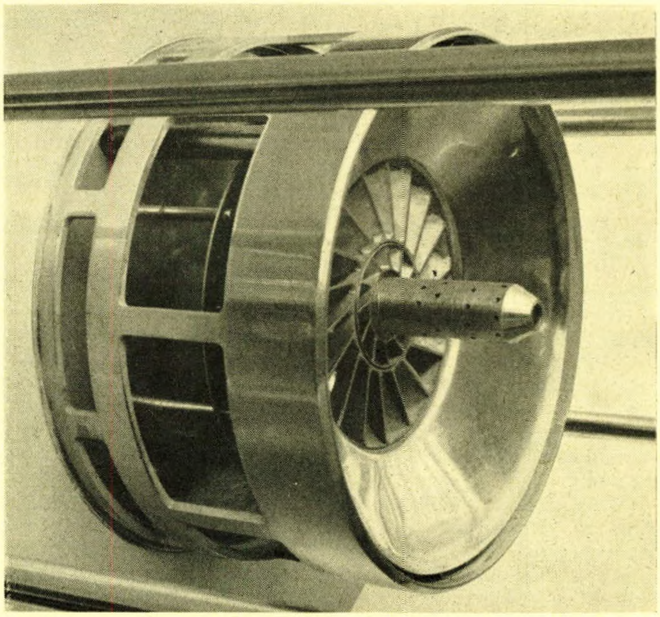


FIG. 47—*"Lancastrian" register (rear view)*

In this type of register, it is best not to use the jet shield immediately surrounding the sprayer as described above in some other applications. Local reverse flow patterns very close to the sprayer shroud face can give trouble with local deposition of carbon, and the small inner swirler is of great assistance in preventing this from occurring. Carbon deposition on the quarl is dealt with in quite an ingenious way by utilizing a flow pattern effect discovered through work on aero gas turbine combustion chambers; that is, the dividing of reaction zone cross section into alternate "leaves" of vortex inflow and vortex outflow. This is achieved by special shaping of the quarl, with which is associated an optimum spray cone angle of no more than 70 degrees. At low loads the butterfly valves are differentially adjusted to give an increased proportion of flow through the inner swirler compared with the outer.

Fig. 48 shows an overall view of the boiler front for the above application. 70-75 per cent thermal efficiencies and

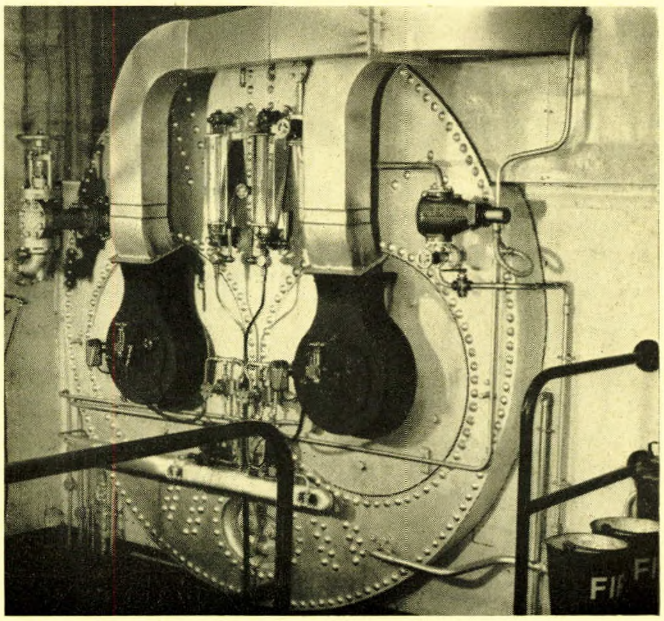


FIG. 48—*Lancashire boiler front with "Lancastrian" registers*

higher may be obtained consistently by means of oil firing on Lancashire boilers of this type, while the same figure can only be obtained with the utmost difficulty if at all on coal fired plant, and efficiencies of 50 and 60 per cent are more typical. These low efficiences can be traced directly to various factors: poor stoking and inconsistent grades of coal which are supplied, as against oil which has a fairly standard calorific value. With the coal fired boiler, the varying qualities of coal may have a direct effect on process work, where in many cases a sustained steam load will hardly be met.

In all cases of oil conversion, familiarization with the equipment will be necessary before the highest performance may be obtained from any manually controlled system, and the solution to this problem appears to be a high performance, fully automatic unit with modulating flame control and controlled combustion air. However, on multiple boiler conversions, manually operated systems have already shown savings by reason of higher boiler efficiencies achieved, and savings in labour costs together with avoidance of coal handling and ash removal.

The various other improvements which result from oil firing are the overall cleanliness and high CO_2 values which may be obtained without smoke. For many years the smoke from coal fired installations has caused some concern, but not until recent years has there been any real effort to limit the smoke formation, and should this legislation be forced further, the case for oil firing certainly becomes much stronger.

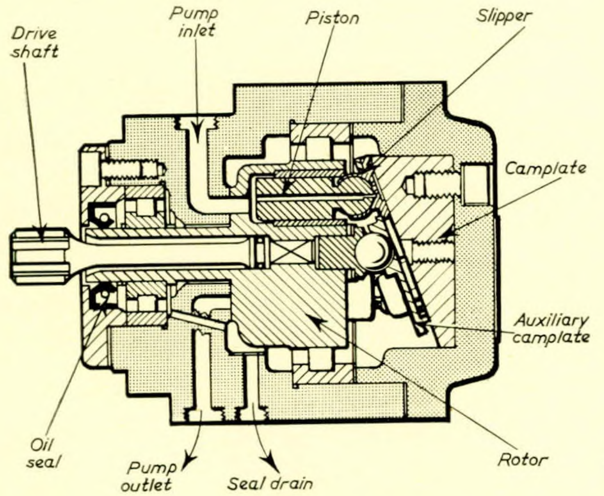


FIG. 49—*F.I.P.60 hydraulic pump (schematic arrangement)*

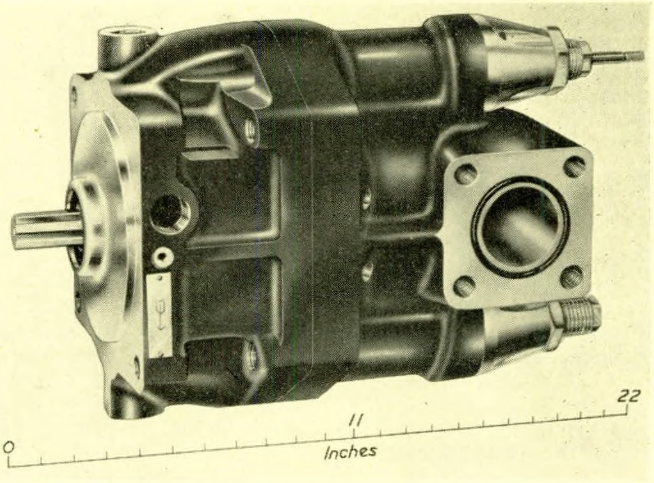


FIG. 51—*I.P. 3,000 hydraulic pump (exterior view)*

11. FUEL SYSTEMS

For combustor or register applications, fuel sprayers commonly require fuel pressures of not less than 200lb. per sq. in. for adequate atomization, where the application does not require a large turn-down ratio. Where a considerable turn-down ratio is required, however, simplex atomizers need much higher pressures. For example, a turn-down ratio of 1·7 requires peak atomizing pressures of up to 600lb. per sq. in.

With heavy fuels, it is usually necessary to preheat the fuel in two stages. The first raises the fuel temperature to one at which it can be economically piped and pumped, and the second stage raises it to temperatures suitable for atomization. In some cases it is possible to pump the fuel at the final temperature but it is usually preferable to place the final heater in the high pressure system downstream of the high pressure pump.

Fig. 49 shows a fixed cam plate pump with five pistons arranged parallel to the axis. It is fuel lubricated and has a silver plated bearing surface. It delivers 60 g.p.h. per 1,000 r.p.m. and can be run at speeds up to 5,000 r.p.m. though its peak efficiency occurs at half this speed. Up to 2,000lb. per sq. in. continuous working pressure is obtainable.

Fig. 50 shows a variable stroke pump with a tilting cam plate servo-operated to follow up the motion of a control lever. This pump will handle oils up to a viscosity of 3,500 seconds Redwood No. I at 100 deg. F. when suitably preheated. It delivers 3,000 g.p.h. per 1,000 r.p.m. and can be run at speeds up to 2,000 r.p.m. Fig. 51 shows an exterior view of this pump.

Fig. 52 shows the I.P.525 pump which is an adaptation of

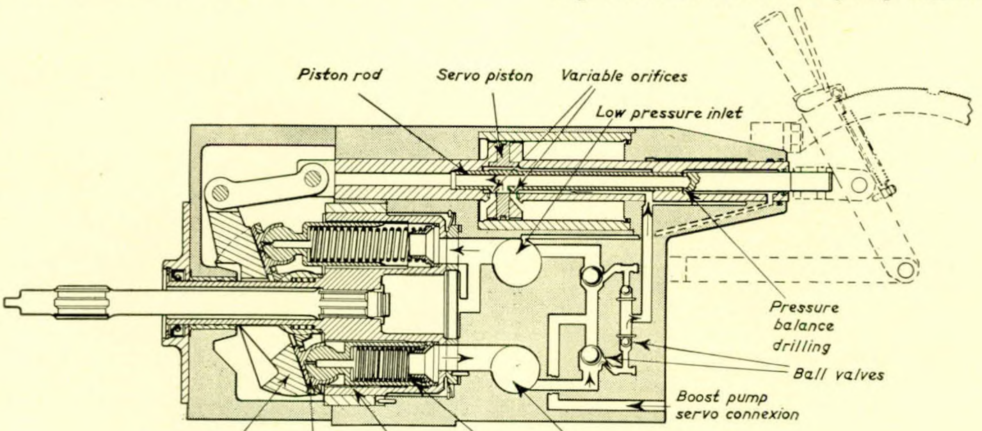


FIG. 50—*I.P. 3,000 hydraulic pump (schematic arrangement)*

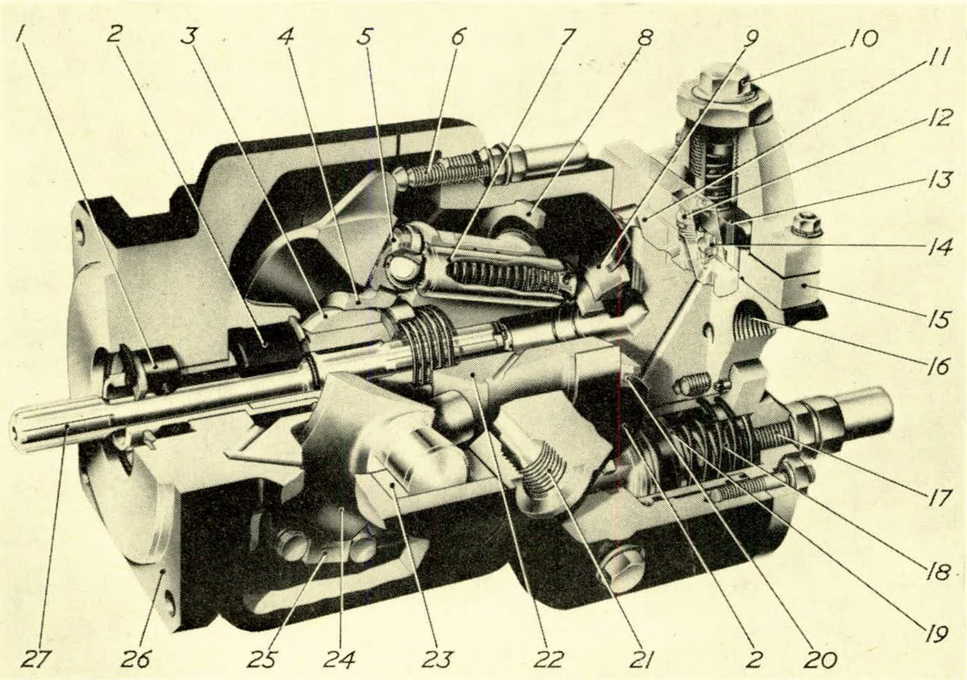


FIG. 52—*I.P. 525 hydraulic pump (perspective cut away view)*

1) Seal; 2) Carbon bearing; 3) Thrust ball; 4) Auxiliary camplate; 5) Slipper pad; 6) Maximum flow adjusting screw; 7) Plunger; 8) Circlip; 9) Port insert; 10) Adjusting screw; 11) Flow reversing plate; 12) Orifice; 13) Rocker lever; 14) Piston and sleeve assembly; 15) Stall valve base plate; 16) Inlet or outlet connexion; 17) Minimum flow adjusting screw; 18) Servo springs; 19) Servo control piston; 20) Retaining spider; 21) Cooling flow connexion; 22) Pump rotor; 23) Trunnion block; 24) Camplate; 25) Linkage; 26) Camplate housing; 27) Splined shaft.

the "D"-size aero gas turbine pump for industrial applications. The pistons are set at an angle to the axis of rotation, and the tilting cam plate is servo-operated to follow the demands of a hydraulic control system. The pump will deliver 1,300 g.p.h. at 2,000lb. per sq. in. continuous rating.

With manually controlled sprayers, using simplex atomizers without turn-down, a pressure relief valve and isolating valve form the simplex control system. Where moderate turn-down is required, simplex atomizers with a pressure control valve, either manually or automatically controlled, is the simplest solution.

For higher turn-down, either duplex or spill atomizers may be used, as indicated in section 2. In the duplex system the pump pressure is controlled by a relief valve, and throttle

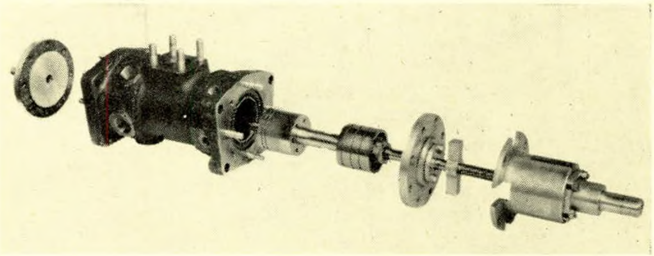


FIG. 53—*Flow distributor for marine registers*

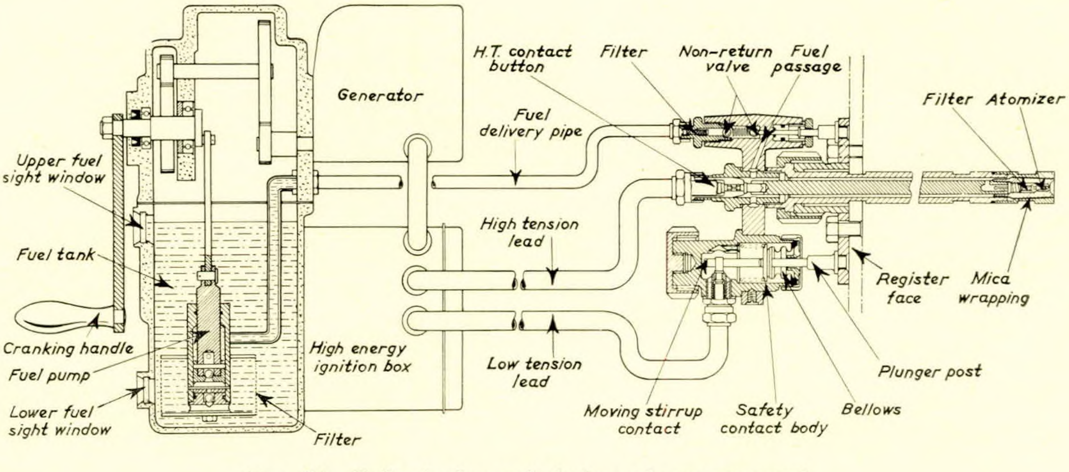


FIG. 54—*Boiler igniter unit (schematic arrangement)*

valves control both pilot and main flow. These valves are in most cases combined into a single unit controlling several sprayers, and accurate calibration is necessary to ensure equal distribution.

In some applications, e.g. a marine boiler front where a group of registers are in simultaneous operation, it is necessary to ensure accurate matching of the flows by means of a flow distributor such as that shown in Fig. 53. This distributes flow to five main and five pilot atomizers in an application of this type. It is machined to diametral clearances of from 0·0003in. to 0·0006in. and the metering slots are stoned to an accuracy of 4 per cent on fuel distribution. The maximum fuel flow capacity of this unit is five times 2,200lb. per hr. at 550lb. per sq. in. atomizing pressure.

Where spill atomizers are used, the control is by a variable orifice in the spill return. There may be one valve for each sprayer, when separate control is needed, or more commonly the spill flows from several sprayers are joined together and passed through a single control valve.

Two systems are used for simultaneous control of air and fuel so as to maintain the correct ratio. In the first, the scheduling system, the valves controlling air and fuel are "ganged" together and the profiles of the valves and/or the profiles in an intermediate cambox are interdependent. The cam box can become complex when it is necessary to provide for operation on only some of the sprayers. The second system senses the air flow in terms of air pressure and automatically adjusts the fuel flow to maintain the correct ratio.

With regard to future development, much of this will probably be the adaptation of well known basic principles to particular installations. There may be a move towards higher fuel pressures and air/fuel ratio controls of the closed loop type. The spill atomizer will probably be used more as the need for higher turn-down increases and registers become better able to operate efficiently under these conditions.

Fig. 54 shows an interesting development of a boiler igniter unit. This is entirely self-contained and comprises a fuel pump and spark generator driven by hand cranking. The output of the generator is stored in a condenser which discharges periodically through the surface discharge plug, giving a one Joule spark across a gap concentric with the atomizer itself. The complete unit is fitted, as will be seen with adequate safeguards to prevent accidental misuse. The igniter can be applied through an access hole of the type shown in Fig. 35.

ACKNOWLEDGEMENTS

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APPENDIX

INSTRUMENTATION FOR GAS ANALYSIS

During the development stage of heavy oil burning equipment it may be necessary to determine the air/fuel ratio pattern in the combustion zone. This knowledge is particularly helpful in the case of a combustor. Gas samples are taken through radial probes which may be inserted to any desired position. The mixture of gas and unburnt fuel vapour is directed through heated leads to a copper oxide furnace and thence to an Orsat type gas analysis apparatus. It is only necessary to determine the percentage of CO_2 (i.e. percentage gross CO_2), and oxygen, the air/fuel ratio being given by

$$0{\cdot}0306\,(\mathrm{C}\%)\left\{\frac{100-\%\,\mathrm{O}_2}{\%\,\mathrm{CO}_2\,\mathrm{gross}}-1\right\}$$

where C per cent is the percentage of carbon in the fuel. A rough measure of combustion efficiency at the various points may be obtained by the use of cooled leads and the omission of the copper oxide furnace when net per cent carbon dioxide may be determined. The ratio $\frac{\%\text{ net }\mathrm{CO}_2}{\%\text{ gross }\mathrm{CO}_2}$ is a rough guide to the variation in efficiency from one point to another.

The combustion efficiency at exhaust may be determined by gas analysis but usually requires more precise methods than that described above. At air/fuel ratios in the region of stoichiometric, an Orsat analysis may be adequate to determine efficiencies with an error of rather more than 1 per cent. As the percentage of carbon containing gases decreases with increasing air/fuel ratio, the percentage of the unburnt constituents becomes more significant and it becomes necessary to determine accurately small percentages of CO_2 and perhaps fractions of one per cent of CO, H_2 and CH_4. Two of the most popular methods are (a) the gravimetric technique and (b) the infra-red technique. In (a) a known volume of sample is passed through a series of weighed absorption tubes and copper oxide furnaces, the gains in weight of the tubes being convertible to percentages by volume of the individual constituents. In (b) the sample is passed continuously through a cell exposed to a beam of infra-red radiation. The absorption of certain bands reduces the heating effect at the opposite end of the tube and this is translated in turn into a pressure change and an electrical capacity change, the latter being measured and calibrated in terms of the percentage of the constituent in question. A separate instrument is required for each gas (viz. CO_2, CO, CH_4). Hydrogen is not determinable in this way but another physical method based on thermal conductivity is available.

The error in the determination of percentage efficiency amounts to about ±0·01 (A/F − 1) in the case of the gravimetric technique and should be rather less with the infra-red method if hydrogen is accurately determined.

Unburnt fuel may be determined separately by oxidizing the sample as it leaves the sampling probe by means of a platinum catalyst, and subsequent determination of the resulting CO_2 by means of one of the above methods. This difference between this gross CO_2 percentage and the sum of the CO_2, CO and CH_4 percentages previously determined affords a means of calculating the weight of fuel per unit volume of sample.

The importance of careful sampling, of course, cannot be over-emphasized. Where possible it is advisable to employ automatic gas samplers—instruments which traverse the exhaust section continuously. In any case the whole exhaust section area should be represented, if necessary, by drawing small equal quantities of gas from a multitude of points.

Discussion

COMMANDER V. M. LAKE, R.N. (Member) congratulated the authors of the paper on a most comprehensive survey of the principles involved in the combustion of fuels of the types in which the marine industry was most interested and on the part they had played in the remarkable upsurge of the oil burning industry since the war.

Sir Donald Anderson, in a memorable after dinner speech to the Institute some time ago, made a remark regarding the "Bath sponge" which he felt absorbed much of the taxpayer's money without much visible return to the marine industry. Much of the work described by the authors had been the result of some small drops of liquid squeezed from that sponge. Whatever the S.M.D. of those drops, here at least was an indication of a desire—a burning one—to advance the combustion art; and it still was an art in many respects.

He would prefer to leave to more able lips than his any amplification of the fundamental details of the paper, and he would limit himself to giving a little of the background of those developments which stemmed from the Admiralty.

The Admiralty during the war began to appreciate the necessity for improved methods of combustion. This came as a result of worsening fuel, increasing wartime operating problems with equipment rapidly growing obsolescent, and the future need for smaller and more compact power plants.

The Admiralty Fuel Experimental Station at Haslar was the source of new developments, and from here sprang the post-war ideas which as a matter of policy were to be further developed and commercialized by industry primarily for Admiralty use, but also, as was now known, for the benefit of industry as a whole.

The advantages of higher operating fuel pressures and improved manufacturing techniques were soon brought home by the achievements in the aero engine field. Later, the requirements for remote operation led to the demand for improved turn-down on the fuel system as a whole. Again, they borrowed from the aircraft industry; and Lucas developed for them the Duplex atomizer which, within its limits of turn-down, had been satisfactory. It was thus with Lucas that the Admiralty began to reap the benefits of aero engine research.

At this time the Admiralty Fuel Experimental Station produced the Admiralty Suspended Flame Register, an example of which was illustrated in Fig. 24. The patents for this form of flame stabilization, i.e. behind a multibladed swirler, were now vested in the National Research Development Corporation, but the Admiralty retained their right to have this type of register made and developed where they wished to meet their own requirements. To meet strategic and financial requirements steps were also taken to "educate" any firms interested in this design. This had been most successful, and many people now had a better understanding of the exacting requirements of the modern highly rated combustion equipment.

He found it somewhat salutary to compare the price of a modern register with that of a small modern car!

The troubles associated with furnace linings led the Admiralty to enter the combustor field, since heat release rates in the aircraft combustion cans seemed to indicate a possible improvement in boiler size and elimination of brickwork. This foray into a new field proved interesting but was finally abandoned because of the inability at the time to burn residuals with any success; largely because, as the authors had pointed out, materials were not yet developed to meet the difficult corrosion problems. However, he was glad to see that this had not deterred Lucas, and apart from boilers fired on distillate, they had now succeeded in finding other applications in industry.

The variable air flow registers illustrated in Figs. 25, 31 and 32 showed another approach to the ideal of good combustion over the power range. This was another attempt on the part of the Admiralty to improve design because they wanted wide turn-down conditions. They tried here to get the air/fuel ratio correct at all times. This again was abandoned, not for combustion reasons, but as being too difficult mechanically. The register itself was becoming too complex.

Figs. 33 to 36 showed combustion equipment produced to Admiralty requirements, illustrating certain features special to their needs. Incidentally, they were not too proud of the pilot register, for, although its performance might be that claimed by the authors, unfortunately it did not have a very long life.

Here he would like to emphasize the importance of *ad hoc* development on the boiler, or one similar, to which the equipment was finally to be fitted. One saw the importance of air flow in the register and Lucas well knew the importance of testing their combustion equipment full-scale. Dr. Clarke had pointed out the importance of air flow to the registers as well as the combustors. Combustion could, however, in highly rated boilers at least, be very greatly affected by inlet flow conditions and by furnace aerodynamics. There was room here for further research.

It would be unfair to leave out the fuel system. The authors had covered this by discussing various combustor and register applications. Incidentally, the development of the little Lucas pump was nothing to do with the Admiralty, but it represented a major advance in oil pumping equipment. These little pumps had been tried at the Admiralty Fuel Experimental Station on distillate fuels—and little was the word beside their Admiralty motor—with success. They had not yet been moulded into a fuel system.

This moulding process must be done. It had been done in the spill systems to which the authors alluded. These had been developed jointly by Lucas and Yarrows to produce a very successful system which was now being fitted in all new construction. Turn-down was of the order claimed, provided, of course, that the maximum individual burner output was sufficiently large. Turn-down, as would be readily appreciated, was largely determined by the minimum quantity of fuel that could be burned. Operation was very simple insofar as the register and control of output were concerned. Unfortunately, the high pressure pumps which had been adopted rather spoilt the otherwise elegant equipment. Perhaps, when the little pump was tied up, it would produce a satisfactory system as regards weight, space and capacity.

With regard to future development, he believed that this must be in the direction of simplification. With the general adoption of automatic combustion controls, the whole oil burning process had become remarkably complex, and just a little beyond the average operator, who perhaps might stay only a short time with any particular equipment.

This might be the price to be paid for improved performance, but one must beware of over-complicating equipment in order to make small advances in one field only. He himself, at the moment, tended to turn from high pressure spill systems towards those which required less complex ancillaries.

Finally, he would like to emphasize the necessity for teamwork if advances were to be made in such fields as these. Dr. Clarke had covered a very wide field indeed, and no doubt the experts in each particular small plot would have a lot to say. But it was the moulding of all these expert ideas into one final system that produced the results. Here indeed the marine and aircraft industries—certainly as far as the Admiralty was concerned—had helped each other to a very great extent since the end of the war.

MR. W. SAMPSON (Vice-President) said that his contribution would be very short and confined to a few generalities.

Knowledge on heavy oil burning had been lacking for a very long time. Designers had to design boilers for all sorts of conditions, and it would be realized how useful it would be to a boiler designer to know exactly for any particular fuel of a certain viscosity the shape and length of the flame and whether the fuel could be completely burned inside the combustion chamber. That was why he valued the paper immensely. He felt sure that if boiler designers and operators would study the paper they would see that a great step forward had been made. It had taken a long time, as he had said, but he thought a great deal more expert knowledge was now becoming available than had ever been available in the past.

The target, in the burning of fuel, was obviously to burn it completely inside the combustion chamber. The authors had pointed out that marine boilers had to burn their fuel in sight of the heating surface, the furnace tubes receiving the greater proportion of the heat by radiation. They had also pointed to the danger of allowing any unburnt fuel, volatile or carbon, to touch the generator surface. They were all alive to the smoke nuisance with its serious effects, particularly in liners. He believed that most of these troubles would disappear when fuel was burnt completely within the combustion chamber. At present this was seldom attained. Smoke was caused by incomplete combustion, and therefore the paper was welcome on this ground alone.

He would suggest that boiler designers should find improved ways and means of burning fuel at much higher heat release rates. Figs. 16 and 17 had interested him greatly. They showed that the speed of combustion was increased as higher heat release rates in terms of boiler furnace capacity were realized, and the consequent great effect on boiler design was obvious. The heat release rates mentioned for Dr. Clarke's combustor could unfortunately not be reached with the open register because the fuel was burnt in different conditions, quite apart from the chemical contents. If twice the present speed could be obtained, with the burning of carbons as well as volatiles, it might be possible to reduce the size, for all boilers had combustion chambers that were far too large. That would not be the impression of most marine engineers today, who thought they were far too small. Fuel had been burned at ten times the present rates of burning in marine boilers, and this had been possible because of improvements based on research, as indicated by the authors.

COMMANDER F. J. RICKS, R.N.(ret.) (Member) stated that he was glad that Commander Lake had clarified the position regarding certain parts of the paper, for he had felt that he must state in defence of his staff and himself that the pictures, Figs. 33-36, represented a design which was developed by, and for, the Admiralty at Haslar, and that to call them examples of the Lucas stabilized flame was a misnomer. He felt, however, that the authors had erred in enthusiasm rather than malice aforethought, and he was gratified that they thought highly enough of the design to wish to adopt it.

He was interested to hear that the authors considered it to be an established fact that the "swirler alone completely failed to produce a reverse flow region", for it was in his experience an extremely flexible medium in the production of equipment for heavy oil burning and rather than lack of reversal he found, since most of his time was spent in the development of swirlers, that he was occupied in preventing too much reversal. He would, therefore, like the authors to state on what grounds they based their statement.

In presenting the paper, Dr. Clarke had stated that simplicity and small costs were the bases on which to design equipment, yet in the "Lancastrian" register forced draught of 6-in. w.g. is used in the primary air supply to burn a small quantity of oil, namely 250lb. per hr. He, on the other hand, had found that it was quite a simple matter to burn 430lb. per hr. in a register, using a simple swirler at a natural draught loss of 0·5-in. W.G.

He would like to know what, in the opinion of the authors, was the advantage of such complicated equipment designed primarily for boilers with large combustion spaces, and in which, therefore, a long clean flame would seem to be advantageous.

MR. B. V. POULSTON said he had had occasion before, he believed, to congratulate Dr. Clarke on his approach to his subject, and on his attempt to rationalize the phenomenon of combustion, employing mathematical principles in bringing together fundamental knowledge about the component processes of an oil flame.

In section 7 of the paper, Dr. Clarke discussed the calculation of various droplet trajectories. Sooner or later in this matter one had to consider the drag of droplets passing through an air stream, and to decide what drag coefficients to use, particularly in the important regions near the root of the fuel spray. He did not believe that droplets knew very much about Mr. Stokes and thought they were more aware of Osborne Reynolds! The first obvious step was to use the very considerable amount of evidence which had been accumulated with solid spheres, and to use the drag coefficients relating to solid spheres moving through air.

Recent data suggested that this was not good enough. Ingebo, in the United States, considering the passage of an evaporating droplet through air, had concluded that the coefficients for solid spheres should be multiplied by 0·8. Hinze, in Holland, considering the deformation of liquid spheres passing through air, had derived factors between 1·1 and 1·3 of the drag coefficients of solid spheres. In the correlation of trajectories with experimental evidence about the spatial distribution of droplets from a pressure atomizer, Mr. Poulston's own work had suggested that an even larger factor of about 1·5 times the drag of solid spheres should be used.

Dr. Clarke had a wide choice of drag coefficients. Would he care to comment on which value he himself particularly favoured?

Having expressed his admiration for Dr. Clarke's approach to the problem, perhaps the speaker might refer briefly to an aspect on which he differed from the authors. The impression was given in the paper that rotary cup atomizers in general produced a uniform size distribution of droplets. There was a photograph of a rotary cup atomizer in the paper which, he would submit, was perhaps rather a particular beast!

Associated with the vast majority of commercial rotary cup atomizers was an air supply passing a high speed stream of air around the lip of the cup. The flow of fluid inside the cup was amenable to mathematical calculation, and a number of sets of flow conditions could be defined. In one of these regions, droplets would spin off the lip of the cup and uniform droplet size might be obtained. In another flow region the fuel shot from the edge of the cup as a continuous film. Thereafter it was impacted by the air flowing around the outside of the cup.

He had had occasion not very long ago to study a number of commercial rotary cup atomizers from this point of view. In every case, evidence was found that the fuel came off the lip of the cup as a film. Therefore, in their mode of operation, there was not very much difference between a rotary cup atomizer and a rather more normal design of air blast atomizer.

He would submit that there was thus no reason to suppose that the droplet size distribution derived from a rotary cup atomizer was significantly different from that of a normal air blast atomizer.

One could also argue, and Dr. Clarke had hinted at this earlier in the evening, that uniformity in droplet size was not very desirable for the combustion of fuel: a reasonable proportion of very fine droplets was probably beneficial for flame stabilization. Dr. Clarke had suggested that perhaps the very large droplets had themselves an important part to play in the flame, although they had been generally regarded as most undesirable. There were the germs of a most interesting argument here which he did not intend to pursue at the moment.

Finally, he would submit that Dr. Clarke's plea for the removal of ash from residual fuels was economically unrealistic. He would refer him also to two papers presented at the World Petroleum Congress 1955* in which evidence was put forward which suggested that the amount of ash in the fuel was not of very great significance if there happened to be any excessive temperature around to initiate corrosion. Perhaps, after all, consideration of the source of the fuel was not all that important.

COMMANDER L. K. D. WOOD, M.B.E., R.N.(ret.) (Member) said that much had been heard that evening of the research and experiments which had been carried out in recent years on heavy oil burning and the equipment produced as a result of such work. This was of great importance to the boiler designer, and—he believed—to marine engineering in general.

Of the many desirable characteristics the boiler designer attempted to include in his design three were of particular importance. First, there was high efficiency to contribute to minimum fuel consumption in the whole installation. Secondly, there was minimum size, weight and first cost of the boiler. Thirdly—and probably most important of all—there was complete reliability in service.

To design for maximum efficiency the boiler designer needed to be as sure as possible of the conditions which would arise in the furnace in service. Boiler and superheater design was not yet an exact science. He felt sure from what little he knew that there was still something of an art about it. If the boiler designer could be reasonably sure of the furnace conditions he would meet—the flame emissivity and gas exit temperature—he was greatly assisted in his efforts to obtain optimum design of generator, superheater and economizer or air heater, as the case might be. If he could not be so sure of the furnace conditions, then he must make allowances and add margins which would detract from the optimum performance and efficiency. Great assistance in this context came from oil burning equipment which produced consistently good and predictable furnace conditions.

As regards minimum size, weight and first cost, a major part of the boiler—the generating section—was designed around the furnace. The smaller the furnace the smaller was this part of the boiler. This contributed greatly to the overall size, weight and first cost of the whole boiler. A reminder had been given that evening of how much needed to be done in marine boilers towards this end.

The furnace must be large enough, however, to ensure that all the fuel required for maximum evaporation was burned wholly within the furnace, with no impingement on tubes and refractories and no flaming through the generator tube bank. All efforts by oil burning equipment manufacturers to ensure a small compact flame were of importance in this context, and something of these efforts had been heard. It was of equal or even greater importance that this compact flame should be consistently obtained in service. A furnace which accommodated the flame during carefully controlled trial conditions was quite inadequate if the burning equipment and the combustion it provided could not be relied upon in service, with the result that long, wild flames impinged just where they should not.

The third major factor, reliability in service, was unquestionably the most important of all. There must be reliability as to good performance and efficiency, to contribute to minimum fuel consumption, and there must be mechanical and physical reliability.

Reliability of performance and efficiency depended greatly on clean heat transfer surfaces. This in turn depended on good combustion.

Mechanical and physical reliability depended on consistently good combustion of all the fuel within the furnace with no impingement. This was especially important with modern high sulphur and vanadium content fuels, particularly when such fuels were used in boilers operating at high pressure and temperature steam conditions. Poor combustion resulting in high superheater tube metal temperatures quickly provided the conditions under which vanadium could attack tubes.

Provided the superheater was judiciously placed in a moderate temperature zone, such vanadium attack would probably not take place under the designed metal temperatures which would accompany good combustion.

One other aspect of reliability separate from that of the boiler which he would like to stress was that of the burner equipment itself. It must be robust to stand up to the exacting conditions of marine service. To put it in a nutshell it must be "crew proof".

In conclusion, the foregoing factors all added up to the unmistakable fact that a great welcome must be given to the efforts of all oil burning equipment designers and manufacturers to improve and to perfect this equipment, so that it produced consistent and reliable optimum furnace conditions and gave mechanical reliability under the exacting conditions of marine service. The efforts behind the paper were a major contribution to this end.

MR. W. KEMP (Member) said that Dr. Clarke and his associates were to be congratulated on the enormous amount of abstruse and painstaking research they had revealed in the paper, particularly with regard to the development of the Lucas combustor, which enjoyed—he understood—a very great measure of success in the aero and gas turbine fields.

Whilst much of the work done in the enclosed combustion field was applicable to open-register design, analogy did not take one very far along the road to burning heavy residual fuels in the combustion chambers of normal boilers, both land and marine, and it was apparent that much more research of this nature needed to be done.

He thoroughly endorsed the remarks of Mr. Sampson and Commander Wood that research of this nature was giving an enormous impetus to the problem of burning residual fuels in boilers, but it was a matter of regret that the authors had not paid tribute to some of the early workers in the field of heavy oil burning who, without elaborate scientific resources and without mathematical techniques, had burned, with a fair degree of success, very difficult fuels and even sludges. Some of these pressure jet and steam atomizing sprayers and registers

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* Section VI/D Preprints 3 and 4, World Petroleum Congress, Rome 1955.

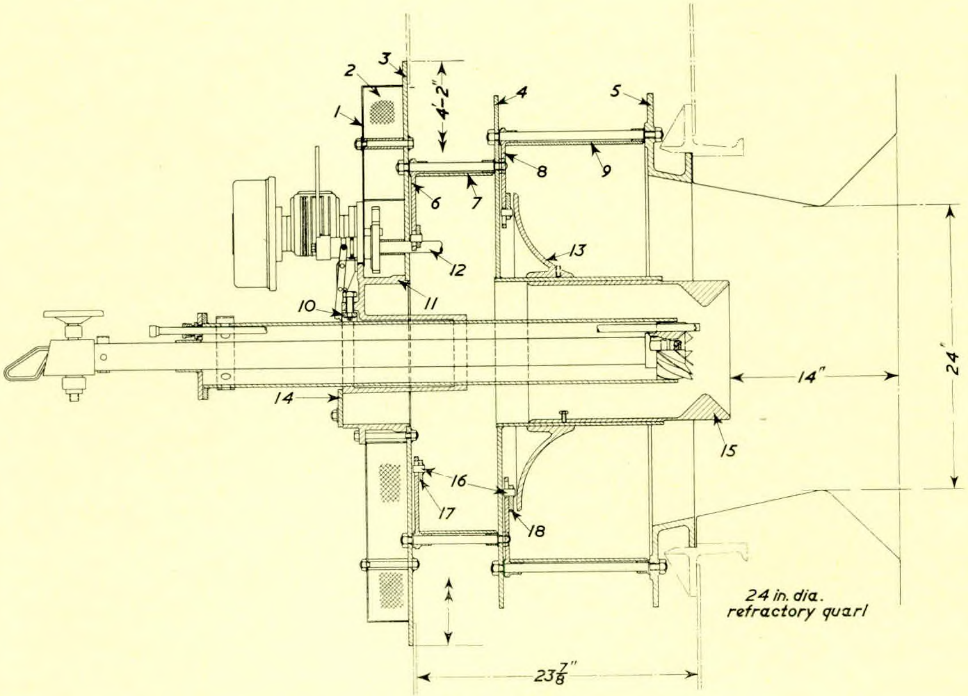

FIG. 55

1) Insulated front plate; 2) Insulating mattress; 3) Front plate; 4) Dividing plate; 5) Back plate; 6) P.A.V. operating link; 7) Primary air vane; 8) S.A.V. operating link; 9) Secondary air vane; 10) Carrier tube clamp; 11) Burner door; 12) S.A.V. operating spindle; 13) Secondary air fairing; 14) Inspection door; 15) Primary air nozzle; 16) Pin for operating air vane; 17) Primary operating ring; 18) Secondary operating ring

were still being used, improved in the light of many years of practice.

Pioneer workers such as W. A. White, Babcock and Wilcox, Peabody, and their contemporaries, were experimenting with swirlers and stabilizers, some of them bearing great resemblances to those shown in the latest register described in the paper, as long as forty years ago.

He had the good fortune to become associated with William Albert White shortly after the first world war, and Mr. White used to propound good register design in the following way:

"Stabilize the flame with as little reversal of flow as possible over as small an area of the throat as possible, and then shoot the air into the oil spray as near to right angles as possible".

This principle was followed successfully by modern oil burner makers. As an example, Fig. 55 illustrated such a register with a primary stabilizing zone and secondary air admission from a common air casing into a convergent-divergent refractory throat.

Typical results on such registers (and there were some hundreds in operation) were as follows: —

Gas analysis 0·5 per cent free oxygen and even less at times, representing CO_2 of over 15 per cent. Air pressure drop through the register, 4·2-in. W.G. Air temperature, 550 to 600 deg. F. The capacity of each sprayer was about 3,600lb. of fuel per hr. at a pressure of 480lb. per sq. in.; fuel temperature, 290 deg. F. Fuel, 6,000 seconds Redwood No. I at 100 deg. F. There were other burners doing this sort of thing today, and he had hoped they might have been mentioned in the paper.

This particular register was used in large steam generators in power stations and was completely under remote control. A servomotor could be seen in the upper left hand side of Fig. 55 which controlled both primary and secondary air vanes. Ignition was of the high energy type, and the ignitor, which could be seen adjacent to the sprayer tip, discharged a spark every 0·5 second with an energy of 16 joules. Sprayer purging was effected by steam or compressed air.

It was also a matter of regret that Dr. Clarke had not mentioned at least three of the advantages of the rotating cup burner (Fig. 56), which was being used with great success on very heavy fuels.

Firstly, the fuel need not be reduced to less than 400 seconds Redwood No. I in the cup. Secondly, the oil pressure necessary was only that which would feed the oil into the cup. Thus, the high temperatures and pressures required to give wide control and to burn heavy oil satisfactorily with pressure jet burners could be avoided. Thirdly, the rotary cup burner had a wide turn-down range. The larger the burner the larger

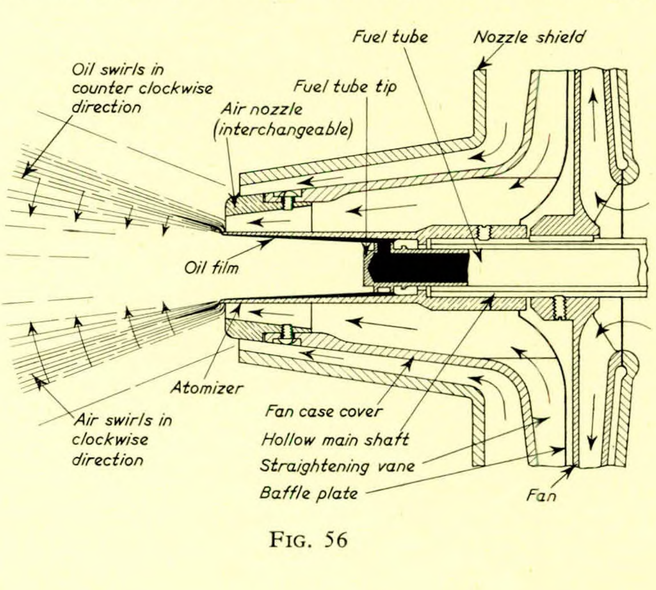

FIG. 56

this range, which could go up to 15:1 with burners of 4,000lb. per hr. or more. It was being used for marine purposes with some success in Germany and Scandinavia. The superintendent of a large German shipping company was reported as saying that he was able, on a 10,000-h.p. job, to manœuvre in dock under fully automatic boiler control and come alongside without hand control of the burners. The turn-down must have been such that the auxiliary steam demand exceeded the steam generation on minimum turn-down when the main engines were stopped. He was not quite sure how this was achieved.

Going along Mr. Sampson's line and assuming that burner makers and boiler makers got closely together so that not only had the burner maker to meet the limitations of the boiler but also the boiler maker the limitations of the burner, it might well be that the marine burner of the future would be a high capacity (two tons per hr. or more) spinning cup burner having a turn-down range of 10:1 or more, fitted to a boiler with combustion chamber suited to the characteristic sausage shape flame of this type of burner. The controls of such burners might be connected into the main engine controls in such a way that their turn-down preceded the shutting in of the manœuvring valve, so that sudden rises in steam temperature, with their attendant danger, might be avoided. It would not seem difficult to achieve, and could eventually prove acceptable in the marine field.

Considerable development had taken place in rotary burners and it was an established fact that the amount of atomizing air required might be as low as 5—6 per cent of the total air required in large burners of this type. The auxiliary fan power was thus not excessive.

To come to practical points, it was nice to see duplex and simplex atomizers with excellent atomizing and turn-down characteristics, and produced with the correct physical proportions and finish to achieve these results. But the usage to which these parts were inevitably subjected, both at sea and on land, resulted in a fairly rapid deterioration of these highly finished parts and their efficiency consequently diminished.

The complication of the duplex atomizer shown could be understood, because it effected considerable turn-down without spill-back, but the simplex atomizer consisted of a number of delicately machined parts which had to be assembled in the correct manner. If they were assembled in an incorrect manner, such as upside down or with parts omitted, the results could be disastrous. Further, the slot/orifice ratio could be altered by operators assembling different swirlers with the same size of orifice plate. Unless there was very careful supervision —and this should be the job of the watch engineers—the flame characteristics could be altered, both as regards atomization and contour of flame. Manufacturers of long experience were reducing atomizers to the simplest practical form and in fact a "one piece" type was being widely used (Fig. 57).

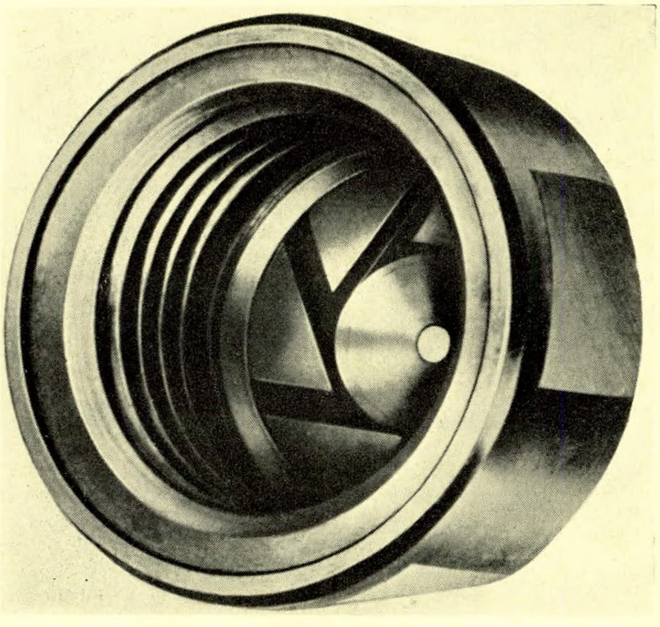

FIG. 57

Regarding pumps, the Lucas proposition of swash plate multi-piston pumps seemed a very complicated way of pumping residual fuels when pumps of a much simpler and more orthodox nature were available. With variable speed control, gear or screw types would appear to give all the requirements for heavy fuel burning.

Lastly, he would like to know what was meant when steam was described as an undesirable medium for atomization, because "it interferes with the kinetics of the combustion reaction". There must be more steam atomizers in use than any other type all over the world, many of them regarded as successful. He would like some elucidation of that description.

MR. J. D. ESKDALE said that on reading the paper he got the impression that the dual air system mentioned on page 150 was a development of the authors' organization but this was not true. Were the authors aware that dual air burners designed and manufactured by others had been operating for some considerable time in a generating station of the Central Electicity Generating Board? They burned 1,000lb. of 6,000-sec. (not 1,000-sec.) oil, with a consistent CO_2 of 15 per cent.

These burners, it was interesting to note, were not fitted with quarls at all; and yet no carbon build-up was seen, and there was no impingement.

Again, with regard to page 153, were they aware that another type of burner using duplex air streams was incorporated in an industrial burner and many hundreds of these burners had been in service for years, burning 6,000-sec. oil with a CO_2 of 14 to 15 per cent, without any carbon build-up or impingement?

Despite the authors' statement that their burners were well above contemporary practice, these other burners achieved a much higher efficiency and greater turn-down without changing atomizers, not with light oils of 1,000 seconds but heavy oils of 3,500 to 6,000 secs. Only last week a snap set of readings taken by a senior official of one of the major oil companies on such a burner, commissioned in a power station several months ago, showed CO_2 of 14 per cent, and a smoke number on the Shell instrument of less than one at 75 per cent loading, when dealing with 6,000-sec. oil.

On page 154, the authors inferred that it would be necessary to incorporate automatic features for optimum combustion, such as flame modulation, controlled combustion air, and so on, on future burners, but these features were all already in use on all the burners he had mentioned.

MR. E. G. HUTCHINGS (Associate Member) said the authors were to be congratulated on a paper which treated the scientific side of oil burning in a most thorough and concise manner. As such, it represented a most valuable contribution to marine engineering, but there was one word of caution. Increased air pressure loss meant increased fan power consumption and the effect of this on the fuel bill alone was quite surprising.

He had had experience with some of the burners mentioned in the paper, particularly the spill atomizers operating in open registers in naval boilers. The range of turn-down experienced with these burners was quite fantastic, but it was doubtful whether they would be attractive to the normal merchant operator, due to the very high power consumption for both the fans and the pumping equipment. This type of fuel system had been considered by his company recently for a commercial application, and it was found that the cost of the plant was four times that of a more normal, wide range, oil burner system. It must be admitted that the range of the more normal system was only about a quarter or a third of that on the spill system: however, it was quite adequate for the job.

The authors referred to spinning cup burners as being very suitable for small outputs. It would be interesting to hear their remarks on the use of this type of burner for large outputs such as 2,500 or 3,000lb. per hr.

One minor point which came to mind when reading through the paper was that the use of a consistent system of units throughout would have assisted the reader.

He was rather surprised to read on page 139 that a long flame was desirable in the case of boilers with registers until, reading later on, he realized that the authors were talking about land boilers, not marine boilers. This, of course, was not the case in marine boilers, neither was it true that radiant heating from the flame to water cooled tubes was essential to the design of a marine boiler. However, the furnace liberation in current naval boiler designs with registers was comparable to that achieved in combustors working at atmospheric pressure. Therefore, one would expect the volume of the furnace to be comparable with that of a combustor, while the size would be about the same. It would therefore appear that there was no advantage over the more usual arrangement from a space point of view in naval boilers. In addition, a considerable quantity of heat was extracted from the gas by the water cooled tubes in the furnace, thus reducing the size of the boiler required.

With regard to preheat of oil, a temperature of 280 deg. F., i.e. 20 degrees higher than that quoted in the paper, was not unusual.

The remarks made by previous speakers about other burners which had been in service for many years were appreciated. In such a comprehensive study of oil burning it was regretted that such a short reference—only three lines—was made to steam atomizing. The authors might well be correct in stating that from a theoretical point of view steam was not such a good atomizing agent as air. But it was his own experience in practice that the converse was true. Also a steam atomizing burner tended to keep the surfaces of the boiler cleaner than any other atomizer in common use. In fact, there was a certain amount of evidence to suggest that steam atomizing would partially clean a dirty boiler and enable the remaining deposits to be more easily removed. This burner would also give a wide range of output sufficient for a ship to be manœuvred under all normal conditions, including entering harbour.

A study of Fig. 18 indicated that the dotted curve for A.M.V.O. plus "Victane" was an exact replica of the full curve for the same fuel with the time scale increased by 150 per cent. Similarly, the dotted curve for A.M.V.O. was an exact replica of the full curve with the time scale increased by 100 per cent. In other words, it would appear that the use of a protective air film did not reduce the total carbon deposit which could be achieved in a boiler operating for extended periods, but merely increased the time it took to build up. It would therefore seem that a protective air film was no great advantage in a boiler operating for extended periods.

It would be interesting to know the maximum output of a combustor similar to that shown in Fig. 23, also the maximum heat release, range, cost and CO_2 produced. One also wondered whether the authors had considered the use of water cooling in a combustor.

With regard to Table III, which indicated heat release rates in typical combustion processes, the percentage pressure loss with poor fuel oil in a boiler with high forced draught, having a heat release approaching one million, was of the order of 0·75 to 1·0. In other words, it was considerably less than in a combustor employed with an industrial gas turbine. This would suggest that the use of a register and furnace was more economical on power than the use of a combustor.

He had heard it said by representatives of more than one oil burning research establishment that the air pressure loss across a register was dependent on the number of registers employed. In other words, if only one register were fitted to a furnace, the resistance for a given air flow was considerably less than when five burners were fitted with the same air flow per register. It was also said by the same representatives that this was not due to leakage or to interference of one register with another. Personally, he could not believe this at the moment, and tests with which he had been associated on actual boilers tended to confirm that the statement was not true. Also, tests on a certain boiler fitted with 5½ registers indicated exactly the same pressure loss as was obtained by the authors' company from an air test on a single register. It would be appreciated if the authors could say whether they had had any experience of this difference of opinion, and could offer any explanation of this conflicting evidence.

LIEUT. CDR. C. H. HUMBY, R.N., said that it was always interesting and usually instructive when experts in one field of development—as the authors are in gas turbine combustion—entered a new field, such as the burning of oil in boilers. Their survey of the present state of progress in the combustion of fuels as it affected combustors and registers was therefore very interesting.

In section 6, on the flow pattern development, Fig. 24 appeared to be a little misleading. This was a sketch of an Admiralty suspended flame register, one of the family of such registers which had been designed and developed by the Admiralty Fuel Experimental Station, using atomizers mostly supplied by the authors' company. This sketch did not show the position of the furnace face of the brick quarl, which was an important dimension and which was, in effect, about 2in. from the front face of the swirler and atomizer. Thus, the quarl, in conjunction with the swirler position, controlled the air flow, and a roughly fixed proportion of air went through the swirler and around it. The atomized spray was at no time markedly controlled by, or approached close to, the brick quarl. In fact, in four years' sea experience with Admiralty suspended flame registers no cases of quarl impingement had ever occurred.

Later, in section 6, the authors called the well known principle of toroidal recirculation in the primary flame zone, the "stabilized flame" principle. He would not have thought that this nomenclature should be applied exclusively to the pattern of Fig. 25, as this pattern was also exhibited by other designs of registers, the Admiralty suspended flame type included, and was thus not exclusive to Lucas designs.

Turning to general comments, he would confine his remarks to high heat release registers, such as those Admiralty designs shown in Figs. 24 and 36. The emphasis in heavy oil burning could not be on primary flame stabilization alone. While this was vital for the success of oil burning registers, there were many other important considerations for the establishment of a sound high heat release flame. An air flow pattern must be established within the furnace which led to a successful and compact secondary flame. In particular, in high heat release registers this must also lead to recirculation of hot gases and combustion products round the furnace boundaries back to the commencement of the secondary flame. Thus the register must be designed in conjunction with the type of boiler in which it was to be used.

The matching of the atomizer with the air pattern was of the first importance. In a recent development at Haslar serious pulsation occurred under conditions where burning should have been excellent. It was finally overcome by using a Lucas duplex atomizer having a different ratio of primary to main fuel output to the one originally used.

With regard to the droplet size of the atomized spray, it had been the experience of his Establishment that the authors' recommendation of an upper limit of 100 to 130 microns S.M.D. was fully justified, and must be adhered to over the whole range of turn-down employed. An insistence on small droplet size could often save one from unforeseen difficulties which could otherwise lead to poor combustion, such as bad air distribution on a particular register.

COMMANDER R. B. COOPER, M.B.E., B.Sc., R.N.(ret.) said he had been associated with oil burning for a long time but he felt the paper was a little off the usual lines. He had had the privilege of lecturing not in London but in the provinces six times to members of the Institute. He had always felt that one wanted to help people to use heavy oil and to overcome the many problems that were known to exist today. The more he looked for a logical line of approach in the paper under discussion, the more he felt he was being led by the authors into a land of some Lancastrian Demon and could not find that this Demon was going to be the king of the road to better burning of heavy fuel oil.

He tried to find it in the first part of the paper in which there were references to the burning of light distillate oils and to a great deal of the work which had been done on these oils in an attempt to relate them and to develop combustion equipment for heavy oil burners. One should say: "Don't let us be mislead by these experiments".

A great deal had been heard about boilers and burner design, but no one had said very much about the quality of the oil. The oil companies were and had been for a long time producing oil and they did know what they were doing. They were producing an oil which was cheap to use. After all, no one really minded what they were burning—oil or water or any other fluid—to drive their ships as long as it was cheap and economical; it was the overall result that mattered. The oil companies gave them an oil which was very good value for money, but oils had become heavier, and one no longer had to deal with oils of 1,000 seconds. One had now to deal with oils of up to 6,500 seconds viscosity and even these might be cut back with a distillate; possibly in the future there might be 25,000-sec. oils. One of the requirements of the Central Electricity Generating Board was that they should be able to burn oils of 25,000-sec. viscosity.

This could only be achieved by learning from the oil companies all about their oils, then by getting the boiler and burner designers to co-operate.

The boiler makers had said they would like very high turn-down. There were a number of points on which he would like to comment. The first was variable output burners. A great point had been made of the difficulty of relating some of the problems and results to practical design, there being so many variables. He assumed that with variable output burners one might be talking about a 10:1 turn-down; then one could start at 40in. through the burner and get down, burning quite well in the ½-in. w.g. region at 8:1, which would give nearly 10:1 turn-down. However, supposing one wished to use 10-in. w.g., which was reasonably high even today at 5:1 turn-down, one could be down to 0·4-in. w.g., so to go to 10:1 the air pressure would be practically negligible.

What percentage of CO_2 was achieved with heavy oils for 10:1 turn-down, using a draught loss through the burner of between 8 to 10in.?

Dr. Clarke had made an interesting point regarding steam atomizers and the kinetics upsetting combustion. He himself found exactly the reverse. When trying to get a large turn-down and good CO_2 at low loads, he found that with only 6-in. w.g. a steam atomizer would give 24:1 turn-down from an output of nearly 3,000lb. per hr. He did not think this was so much a science as an art. The velocity of the particle seemed to make it burn more completely and high CO_2 was achieved.

On special high turn-down, pressure jet burners using 6,500-sec. oil, a 10:1 turn-down had been achieved with good CO_2 readings. A spill burner designed for 10:1 turn-down with 3,500-sec. oil came down to only 40lb. per hr. through the burner, and it still gave CO_2 of about 12 per cent.

He had yet to see a combustor that worked well on heavy oil, even 200-sec. oil. If there were a combustor that would burn 200-sec. oil for any length of time he would like to know about it. Otherwise during the last twelve months a great deal of his time had been completely wasted in trying to burn 20 gal. of oil an hr. in a tube 11in. in diameter. Success had been achieved using a blast-type burner but the work had only been necessary because combustors would not burn heavy oil.

Spill burners of the type illustrated on the suspended flame principle were operating successfully in power stations, but only over a small range of 2:1 output. They were operating at 4-in. draught loss and did not seem to make any carbon. CO_2 was high.

One of the reasons one did not want to burn over a wide range was getting automatic equipment to keep air/fuel ratios over a large range of power. It was easy to design an air/fuel ratio control which would control over 3:1 but he would like to know whether there was any experience of air/fuel ratio control over 10:1 and still preserving good CO_2.

Mr. A. B. Pritchard said there were two aspects of the use of oil fuel for boiler firing that had not yet been mentioned —the necessity for correct storage and handling, and the assessment of the completeness of combustion by examination of the type and quantity of "stack solids" carried forward in the products of combustion.

With regard to the former, on page 139 of the paper a brief reference was made by inference to storage in the passage referring to the water content of oil. Reference was also made at the top of page 140 to recirculatory systems. Speaking from the industrial viewpoint, it was most important that oil fuel was stored correctly, with proper provision for the removal of water from storage and service tanks by means of adequate sludging facilities. The provision of proper heating equipment in storage tanks and the maintenance of correct storage temperatures were also of importance in ensuring the highest degree of separation of water from oil.

Where an oil handling system required the circulation of large quantities of hot oil so that a considerable amount was returned to the suction side of a pump, considerable care was necessary in the design of the storage and handling equipment. The most important point was that the pressure on the oil at the heel of the pump would be sufficient to inhibit vaporization of trace quantities of water that might be present. For example, if the oil were returned at a temperature of 260 deg. F., then the absolute pressure at the heel of the pump must be 40lb. per sq. in. If the pressure were reduced below this, then inevitably steam would be produced, or if the oil were perfectly dry it was possible that oil vapour might be produced, which would lead to pressure fluctuation on the delivery side of the pump.

Where the natural head imposed by the oil in the storage tank would not provide adequate pressure at the suction side of a circulating pump, it might be necessary to provide two pumps, the first drawing oil from the storage tank and supplying it to the second pump at the necessary pressure to overcome any water or oil vaporization. The recirculated oil could then be returned between the two pumps.

Referring now to the measurement of stack solids, it was suggested that the users of equipment, even if not the designers and boiler makers, were very interested in the quality of combustion in respect of stack solid production, because this was perhaps the most important factor in the maintenance of boiler efficiency over long periods of operation. It was no use operating with very little excess air if the result was going to be that the efficiency of heat transfer to the secondary heating surfaces of the boiler were impaired by soot deposits. It was very easy to lose up to 6 per cent of boiler efficiency by this means.

It was suggested that a note could usefully be incorporated in the appendix of the paper to cover this matter, and also that a standard might be offered in respect of the weight of solid material that could reasonably be expected in the products of combustion leaving the boiler. His (Mr. Pritchard's) company had suggested that a reasonable standard would be 0·05 per cent of the fuel burnt. Perhaps the authors of the paper would care to comment on this suggestion.

Correspondence

COMMANDER R. B. COOPER, M.B.E., B.Sc., R.N.(ret.) was afraid he could not see that this paper had made any contribution to the burning of heavy fuel oil, in spite of the impressive diagrams and curves used, and the impression he had was that the authors had accumulated data on burning distillate fuels, but, possibly because of their lack of appreciation of standard current practice with heavy oil burners and marine boilers, had been unable to correlate this data usefully to the burning of heavy oil.

He feared that the paper might be harmful to the designers and users of heavy oil burning equipment, for certain statements made were contrary to the findings of designers who had made a long and careful study of the subject. As an instance of this, on page 139 it was implied that in the case of boilers with registers a long flame was required and a comparatively narrow cone angle sprayer was therefore employed. He was sure this remark, without qualification, would be contrary to the experience of most boiler designers and seagoing engineers since for some years now emphasis had been laid on producing shorter flames. Possibly the authors were thinking in terms of Lancashire boilers and should have qualified their remarks to this effect.

As one of the requirements of higher heat release was obviously the finest possible atomization, he would think it would follow that a wide angle sprayer should be used, for it was well known that for atomizers of equal output at corresponding pressures, wide angle sprays were finer in droplet size than those with narrow angles. The authors would know of the work carried out for the Admiralty during the war by Sir Geoffrey Taylor, Dr. Watson and others and of the theoretical calculations made of dimensions for atomizers which would give the best results. He felt that this question of relationship of particle size to the optimum cone angle of spray was one of the reasons why 85-deg. to 95-deg. atomizers were used in combustors where with the high heat releases the finest possible atomization was required.

The statement that droplet size must be carefully controlled at all operating loads was a little confusing, for the flame volume not only depended on droplet size but also on draught loss through the burner.

He did not agree with the authors' statement that the highest oil preheated temperature in common usage was about 260 deg. F., for there were many plants in use burning oil at temperatures of 300 deg. F. and over. It would appear that the author's work had been limited to oil of 1,000-sec. Redwood I viscosity at 100 deg. F. with one or two isolated references to 3,500-sec. oil, whereas of course 6,500-sec. oil was in common use today and it was considered by most people good practice to design future equipment for this grade of oil.

The authors left him wondering as to their experience with heavy oil burners by their remarks concerning the way in which a rotary cup atomizer works and also by the statement that steam as an atomizing agent was an undesirable medium because it interfered with the kinetics of the combustion reaction. With the burning of heavy oil there were many reasons why extremely good burning could be achieved over a wide range of turn-down with steam atomization and if a steam atomizer could be designed such that the quantity of steam required for atomization was acceptable to the plant designers, then it had been found in practice that excellent results could be obtained by this method. There were many reasons why a steam atomized system could give extremely clean boilers, particularly when operating at low powers.

After discussing at some length flow pattern developments and flame stabilizing zones, the authors stated that the use of a control toroidal recirculation of the type described for the purpose of flame stabilization was known as a stabilized flame principle. He would remind them that the stabilized flame principle had been known for many years and had in fact been used by a number of oil fuel burner designers over that period. He would ask the authors in just what way the stabilized flame principle of the Lucas burner differed from that of any burner in use today, for any oil burner of whatever construction, design or manufacture relied for its stability on the reaction of some form of circulation immediately in front of the atomizer. It was well known that the stabilization of the point of ignition of any burner also depended on the absolute rate of flame propagation of the burning fuel. If by the "Lucas stabilized flame" was meant controlled toroidal recirculation, then he thought the authors would be far better to describe this as a means of stabilizing flames rather than the "Lucas stabilized flame" principle. If they meant that the Lucas stabilized flame principle was one incorporating mechanical features shown in Figs. 25, 31 and 32, then obviously registers referred to in Figs. 24, 33, 35 and 36 did not incorporate these features.

They had been told of pilot registers burning 200lb. of oil an hr. with a draught loss of 1 to 24-in. w.g. Would the authors state how these burners worked over this large range of air pressure and whether satisfactory results were obtained?

There were many other points about which he was critical, a few of these being:

(1) The statement that " a spill line is not a disadvantage since a recirculatory circuit has to be provided, even with simplex or duplex atomizers, in order to obtain the preheat when running at low flows". This was not true, as there were many hundreds of simplex pressure jet installations where hot oil was not returned to the pump suction under running conditions.

(2) The showing in Fig. 13 of an improved form of duplex atomizer in which two concentric sprays were entirely separate and the statement that although there was little experience of operating this type of atomizer on heavy oil, there was no reason why a turn-down of 5 to 1 should not be achieved. He could see many reasons, for he believed there would be practical difficulties in its manufacture and he could picture that after one or two cleanings in the boiler room, or after a few hundred hours in use, it might give a turn-down ratio of 5 to 1 but the quality of the atomization over this range would possibly be little better than a pressure jet.

(3) Reference was made to turn-down ratio on atomizers but very little to turn-down ratio on air. If one was to achieve a 10:1 range on atomizers, then presumably unless high percentages of excess air were accepted at the low loads or air quantities which could possibly blow unburnt oil away from the flame on to the boiler tubes, then draught losses through the burner would have to vary by as much as 100:1. If one assumed that a reasonably high draught loss through the burner was 10-in. w.g. at full power, then this meant 1/10th in. at 1/10th loading, an air pressure at which it was difficult to obtain control or good combustion. For a long time now it had not been the design of wide range atomizers which had limited the turn-down range but the design of wide range air registers, about which they were told nothing in the paper.

(4) Had the authors had long practical experience of running pumps on really heavy oils of 6,500-sec. at 1,000lb. per sq. in. and above? If so, what would be the wear on the pumps? Did the authors find so much difference in quality of combustion at 1,000lb. per sq. in. compared with 600lb. per sq. in. to warrant the extra power and pump wear?

(5) The purpose of the flow distributor for spill burners for marine registers was not clear to him. Was this merely an accurately machined device to compensate for atomizers which were not made to such accurate tolerances?

(6) On the subject of heat release they were told of burning with high draught loss at 10^6 B.t.u./cu.ft./hr. He would like to have seen a diagram of the burner used. The high heat release register developed at Haslar was now released for publication he believed and would have been of interest to readers.

To sum up therefore one felt that the authors had not contributed anything constructive to help others with the design of oil burning equipment, nor to help those who had to use such equipment to make their selection of the various proprietary types offered. One was left wondering exactly how much original development or design in the field of the burning of heavy residual oils had in fact been the original work of the authors.

Mr. R. F. Darling, B.Sc., commented that prior to the second world war the development of oil burning equipment of all types was carried out mainly by empirical means. Considerable fundamental research went on in universities and elsewhere but attempts to relate this to practical applications were virtually non-existent.

The advent of jet engines, ram jets, etc., and the need to extend their performance to the utmost limits had brought about a most welcome change in this situation, and in these applications the linking of theory with practice was now an essential part of the development of improved apparatus. This type of approach however was still something of a novelty in the field of heavy oil burning, and it was therefore both stimulating and useful to find a leading authority on aeronautical combustion turning his attention to the burning of heavy oil.

In research work it was always essential to be on guard against the temptation to read too much into one's theories, and several passages in this paper gave the impression that the authors had been guilty of this. He referred in particular to Figs. 16 and 17 and the conclusions which had been drawn therefrom. In presenting the paper, Dr. Clarke emphasized that these diagrams were the essential starting point in the design of his combustion equipment. The general conclusion which they gave was that with the standard of atomization and other parameters constant a distillate such as gas oil would burn in something between one-half and one-sixth of the time required by a moderately heavy bunker fuel. One would thus expect—and the authors evidently did expect—that if a combustion chamber running on bunker fuel were changed over to gas oil, keeping the fuel quantity and the standard of atomization constant, the flame would diminish to less than half its original size. In his experience this was by no means the case.

The main difference between heavy fuels and distillates was that the former could not be burnt at such high intensity; an attempt to burn bunker fuel in an aircraft type combustion chamber, even with the stipulated degree of atomization, would result in incomplete combustion and the build-up of deposits. An altogether larger type of combustion chamber was required and the air and gas velocities must be reduced, resulting in a decrease both of pressure loss and combustion intensity. When such a chamber had been developed to burn heavy fuel satisfactorily, however, it had always been his experience that it ran on distillate fuel with a virtually unchanged length of flame. At Pametrada they had run a marine gas turbine on fuels ranging from kerosene up to 3,000-sec. fuel oil with only marginal changes in flame size at a given condition. One might thus summarize the practical experience by saying that many chambers designed for distillate fuel were quite incapable of burning residuals, but a chamber which burnt residuals satisfactorily would also burn distillates with very little change in flame length. Would the authors please state whether they had ever observed a six-to-one or even a two-to-one change in flame length on changing over from a heavy to a light oil?

This brought him to the question of the build-up of deposits. The authors described a series of experiments designed to evaluate the carbon forming propensities of various types of fuel, but none of the fuels in question was a residual, and it was clear that the combustion chamber used in the experiments must have been specially designed to give measurable carbon formation under the conditions of the test. To apply the results of these experiments to the burning of heavy fuel did not seem to be justifiable, and the suggestion that deposit formation could be prevented by the film of air which was also used for cooling was certainly not borne out in practice. With heavy fuel oil the formation of deposits was usually the result of unburnt fuel striking the chamber wall, and one could see from Fig. 20 that with particle velocities of, say, 100ft. per sec., the film would require to be about 1-in. thick to keep a 20-micron diameter particle from reaching the wall. This was quite unrealistic. Internal films were useful for cooling the chamber wall, but a chamber which had to rely on them for preventing the build-up of deposits would be most unlikely to run satisfactorily for very long.

Fig. 23 showed a most interesting and ingenious design of combustor, but it was questionable whether the application of this device to a boiler could lead to any overall improvement. In the normal boiler about 50 per cent of the heat transfer to the tubes was by radiation, and it followed that if the highly radiant part of the flame were confined within a combustor, correspondingly more heat must be transferred by convection. This required an increase either in the surface area of the tubes or in the gas velocity across them. In the one case the space saved by more intense combustion would be taken up by an increased number of tubes, while in the other the boiler would be less economic, due to increased fan losses. Would the authors please say in what types of boiler and for what applications they would advise the use of these combustors, and what economic advantage they would expect to derive from them?

The design of register shown in Figs. 25, 31 and 32 was extremely interesting, and the accompanying description of how the configuration was developed was an excellent example of how the techniques of aeronautical research could be utilized in industrial and marine applications. The test facility shown in Figs 43 to 45 should enable further improvements to be made very rapidly. On the fuel system side, however, one wondered whether the authors fully appreciated the need for the utmost simplicity in marine applications. Sprayers with such relatively large flow numbers required correspondingly large diameters of swirl ports and outlet orifices, and with care it should be possible to manufacture them so as to give reasonably well matched flow characteristics. The flow distributor shown in Fig. 53 could then be dispensed with, thus giving a considerable saving in cost.

Despite the above criticisms on points of detail, he felt that this paper deserved a warm welcome for the sake of the attitude of mind which underlay it. The application of theory to practical cases and the feed-back of practical experience so as to improve the theory is a normal procedure in most fields of technology, but had hitherto been far too rare in heavy oil burning. This was a case in which it was much easier to criticize than to act. In offering the above comments he was very conscious both of the difficulties with which the authors had been faced and the skill and experience with which they had tackled them.

Mr. G. R. Gray (Associate Member) thought the authors were to be congratulated on their efforts in this paper to correlate existing data and experimental results in an attempt to rationalize the design of oil burning equipment. He thought it would be most difficult to disagree with their basic conclusions but he was sure that they would agree that the design of oil burning equipment remained as much an art as a technique.

There were one or two points on which he would be pleased to have further comments from the authors.

Fig. 9 showed a most interesting set of curves but it was rather misleading when one considered the title of the paper, "Heavy Oil Burning". These curves had apparently been constructed using an oil viscosity of 2 centistokes and therefore gave much smaller droplet sizes for given pressures than would be obtained with a residual fuel heated to give a viscosity of say 15 centistokes; e.g. with a flow number of 10 and viscosity of 2 centistokes, a droplet size of approximately 100 microns could be obtained with an oil pressure of 200lb. per sq. in. To obtain this droplet size with oil of a viscosity of 15 centistokes would require an oil pressure of approximately 600lb. per sq. in.

It would be interesting to know the experimental techniques used by the authors to measure droplet sizes and whether these experiments covered the full range of flow numbers quoted or were the higher flow number results obtained by extrapolation. If the results were extrapolated, was any attempt made to estimate the possibility of increased droplet sizes due to the probability of collisions between droplets being increased.

On page 138 the authors stated that atomization with a rotary cup resulted in a uniform droplet size. Whilst this was true with the laboratory type of rotary atomizer it was not so certain in the application being considered wherein the combustion air might be a major factor in atomizing the fuel.

On page 141 it was stated that steam was not considered a satisfactory atomizing agent but steam had been used successfully for many years for this purpose and there had been suggestions that it had advantages over air for certain applications.

The use of a protective air screen to prevent carbon deposit was a very convincing argument, but the curves in Fig. 18 were not so convincing and might even be slightly misleading. If one took any pair of curves with and without air film it was found that carbon deposit after 40 min. was about 7 to 1 in favour of the air film but after 120 min. this ratio was reduced to little more than 2 : 1; in other words the curves were rapidly converging. It would be most interesting to have these curves drawn for a period of, say, 500 hours, which would be a more realistic figure than two hours.

The authors made a statement on page 144, viz: "The feature which distinguishes a register from a combustor is that there is no lateral or longitudinal control of the flame generated by a register", which was a fact that was not always fully appreciated. It followed from this statement that whilst the shape of flame in the vicinity of the register could be controlled by the register, the shape of the remainder of the flame depended more upon the shape of the furnace, gas pressures and gas off-take positions than on the register design.

It was interesting to note the authors' statement (page 144) that the method of forming a flame stabilizing zone on the registers illustrated in Figs. 24, and 33 to 38, using an isolated swirler only, was not the optimum method, and one wondered whether it was considered to be the optimum method for boiler firing.

Table III would have been very interesting if it had been complete; that was, if the figures of air pressure drop had been given for "boiler firing". The figure of 1×10^6 for "boiler firing: high forced draught" could hardly be called a typical value and it would be interesting to know where the boilers with this heat release rate were situated.

On an investigation in which he was concerned recently, an attempt was made to correlate Δp against combustion intensity (i.e. heat release rate based on flame volume) using figures obtained from existing boilers. Whilst this method was rather rough in some respects the results plotted quite well and from this it appeared that the heat release rate was proportional to $(\Delta p/P)^{0\cdot75}$ rather than $(\Delta p/P)^{0\cdot5}$. Using this correlation to estimate the pressure drop to give a heat release rate of $1\cdot0 \times 10^6$ (approximately equal to $1\cdot5 \times 10^6$ combustion intensity) a pressure drop over the boiler register of approximately 45-in. w.g. would appear to be necessary.

On page 150 the authors claimed a performance well in advance of contemporary practice for one of their registers which utilized a primary air supply of 6-in. w.g., a secondary induced air supply of 0·52-in. w.g. and an oil atomizing pressure of 150lb. per sq. in. in order to burn quantities of oil between 250 and 470lb. per hr. The resulting exhaust gas CO_2 of some 13·3 per cent did not appear to be outstanding and it was felt that several oil burner manufacturers could equal this performance on comparable registers.

In finally assessing the paper one might say that the authors had defined certain salient features which must be inherent in the design of oil burning equipment for satisfactory combustion and then attempted to find a rationalized method of design to obtain these features. This rationalization of method was the aim of all designers but it should be acknowledged that all existing designs of oil burning equipment must, as proved in this paper, involve the salient features required, whether these had been arrived at by a rational design method or by "trial and error" backed by experience.

The one other feature of this paper which the authors might like to comment upon was justification of cost. The design shown in Fig. 35, for example, was doubtless much more expensive than the equipment which was normally supplied and that showed the register only. If high pressure fuel pumps, spill systems and high air pressures were also involved, then the justification for the extra cost and maintenance might be very difficult to prove. If this were considered in conjunction with the unskilled operators, who probably changed every few months, it might be thought that one of the first principles of design had been overlooked, namely, simplicity.

Mr. P. Lawrie, B.Sc., wished first to compliment the authors on the thoroughness with which their work had been carried out and to express admiration for the test rigs which they had available. However, he would criticize the choice of title for their paper, which, far from forming a review of the methods of combustion of heavy fuels, seemed to him to deal purely with one manufacturer's work on pressure jet burners, together with fleeting references to two other methods of burning heavy oils.

It was a pity that in a paper of such general title no mention was made of low pressure air burners, whilst only fleeting mention was made of rotary cup burners and steam and high pressure air burners, all of which types were used extensively in the burning of heavy liquid fuels. Work on the combustion of heavy fuel oils, which had been in progress for many years now and had been carried out at a large number of firms, was still being continued by those firms. The company with which he was associated had quite extensive test facilities for combustion research on a wide variety of types of heavy oil burners, including pressure jet, low pressure air, rotary cup, and medium air pressure burners for land and marine purposes.

Turning to pressure jet equipment, many manufacturers of oil burning equipment had carried out, in recent years, considerable investigations into the combustion of heavy oils, particularly with reference to pressure jet burners applied to marine watertube boilers, and the results of their work were quite impressive. By better understanding of the processes of atomization and air register design, it had been possible to meet all the requirements of the boiler manufacturers without the necessity of providing complex and expensive equipment, so that today at least one private manufacturer could claim to be able to fire completely satisfactorily boilers of advanced design having short combustion chambers, and this when using air pressure drops much lower than those mentioned in the paper. For example, 1,000lb. per hr. of 3,500-sec. fuel per burner was burned completely and without smoke in a combustion chamber approximately 7ft. long with a flame length of 6ft. and CO_2 values of up to 14 per cent with an air pressure loss of 2·5-in. w.g. and an air temperature of about 250 deg. F. Heat release in the combustion chamber, based on total volume, was about 120,000 B.t.u. per cu. ft.

It would be interesting to know what exactly was claimed by calling a burner a "stabilized flame" burner, since the days when flames were stabilized other than aerodynamically were some way past and indeed a stabilized flame was an absolute necessity.

With regard to marine pressure jet burners, it did seem that at present the vast majority of shipowners did not require wide range types, since their vessels operated between ports at sensibly constant speed and power. Changes of oil throughput, therefore, were only normally required when manœuvring in and out of port, and the high turn-down ratios associated with spill type and duplex atomizers would only be useful for a very small part of the ship's service life. In any case, when manœuvring, there was adequate staff in the boiler room to enable atomizer changes to be effected. With wide range pressure jet equipment, the capital cost and the operational cost was higher than with the simplex type. Dealing with operation, to take full advantage of a turn-down ratio of, say, 8 : 1 and to ensure efficient combustion over the whole range, it would be necessary to employ combustion air fans of high power, since assuming the air throughput to the burner to vary as the square root of the pressure loss over the register and referring to a fixed type of register, as shown in Fig. 35 of the paper, the ratio of air pressure losses over the register required would be 64 : 1 from maximum to minimum. Now, if one assumed that ½-in. w.g. was required at minimum flow, it would be seen that the maximum output required 32-in. w.g. of fan pressure purely as loss over the register. The operating cost of a fan capable, say, of providing air for combustion to a 50,000lb. per hr. watertube boiler, would be extremely high, since it would be supplying approximately 12,000 cu. ft. per min. at a full load pressure capable of overcoming losses through the boiler system itself, as well as the air pressure loss over the register. In addition, the boiler air casing cost would be extremely high. Admittedly, with such air pressure losses over the register at full power, very high heat releases would be obtained, probably of the order of 1,000,000 B.t.u. per cu. ft., and this might result in boilers of smaller dimensions than at present, but except for naval practice, such high performance figures had not been asked for by marine engineers. In view of the high capital and operating costs of such equipment, it was felt that merchant vessel owners were unlikely to demand such performances. The authors' opinion on this would be appreciated. With the present heat releases and burner outputs applicable to marine watertube boiler practice, there were many firms who could provide satisfactory equipment.

Dealing with pressure jet atomizers, these, of course, were precision instruments and should be handled as such. However, it was unfortunately true that a delicate atomizer might be handled equally carelessly whether its cost was £1 or £50, and damaged atomizers, whether they were originally cheap or dear, could produce equally bad results. This would seem to suggest that the object of the designer of marine pressure jet equipment for merchant navy practice should be to provide atomizers of sound theoretical design and good practical construction with, of course, high quality finish at a reasonable price. This was possible and had been done by at least one well known manufacturer. The cost of replacements of atomizers due to maltreatment was thus not high and, in fact, it was recommended that atomizers be replaced at regular intervals to ensure that performance of the oil burning equipment was maintained.

Dealing with the burners described in the paper, it appeared that the marine registers shown, although complicated in construction (by the bellows arrangements, etc.), were basically of reasonably conventional design. The land registers were certainly most interesting and appeared to be basically designed as low pressure air burners with pressure jet atomization, and with induced draught supply of 50 per cent of the air requirements. One would think that the running and installation cost of such burners would be high, since high pressure oil piping and pumps and heaters were required, together with fairly large capacity low pressure fans. Some information on these costs, as compared with other types of known oil burners, e.g. rotary cup, low pressure air, would be interesting, and perhaps the authors would be able to supply it.

CDR. J. SIDGWICK, R.N., noted the authors' admission that the mechanism of the disruption of a liquid stream was not yet fully understood. Might he suggest that it was illuminated if the primary role of surface tension was recognized?

The process of atomization had two stages. First, the application of energy to the liquid to force it into a state of high surface energy; in other words, to eject it from the atomizer, whatever its type, in the form of fine filaments or a thin film. Secondly, to induce the liquid to revert from this state to a lower (but still high) state of surface energy, which it would do naturally under the influence of surface tension.

The lowest state of surface energy for a given volume of liquid was, of course, a single spherical drop, but any filament or film could and would deform under the action of surface tension into a collection of droplets whose total surface energy was less than that of the original, the energy lost being absorbed in viscous resistance as the liquid was deformed into droplets.

The size distribution of these droplets, which was of more immediate concern than the mechanism of their formation, would depend not only on the surface tension (without which they would not form) but also on the density and viscosity, the initial dimensions, velocity and turbulence of the film, and on the external disturbing forces from the surrounding medium.

He would therefore suggest that a study of the interchange of energy from initial pressure and kinetic energy to surface energy and its partial loss in viscous deformation of the liquid might be rewarding.

On another point, the authors stated that in swirl atomizers the oil was discharged with a rotational motion. This must not be interpreted to mean that the cone rotated as a whole. Each particle of oil issued with a tangential and axial component of velocity and immediately thereafter pursued a straight line, thus generating a surface which was in fact a hyperboloid, not a cone, *vide* Fig. 3.

The angular velocity of the surface thus decreased as the radius increased, preserving constant angular momentum.

MR. J. D. WELLS wished, before commenting in detail upon the paper, to thank the authors for the great effort that they had made to write a paper on the subject of oil firing, a subject on which very few papers were written. Perhaps it would be an encouragement to all engaged in the manufacture of oil firing equipment to write technical papers on this very controversial subject.

Concerning the method of atomization of liquid fuels, the authors indicated a preference for the swirl atomizer method. This was probably due to the acceptance in the past of this system by users in Britain, particularly in the marine field. There was little doubt that, providing the user did not want a controlled air/fuel ratio and that he was prepared to change atomizer tips to vary the firing rate and in general to make continual manual adjustments, then the simplex pressure jets or swirl atomizer system was an attractive one from the point of view of simplicity, but it did demand a skilled boiler supervision staff. However, more interest was now being shown in oil firing equipment, where the control was either automatic over a large range of burner output or where single lever control of air and oil quantities was obtainable. This was particularly true where just one or two burners were fitted to large watertube boilers, which was justified on the grounds of lower cost and reduced maintenance.

Once one considered these applications, the pressure jet system was at a disadvantage from the cost and reliability point of view, compared with the rotary cup principle at atomization, for the following reasons:

1) The viscosity of the oil used in the pressure jet system of atomization must be about 70 S.R. 1(15 c/s), and to achieve this viscosity, heavy fuel oil must be heated to about 260 deg. F. At fuel pressures below 20lb. per sq. in. gauge, the water in the fuel, which might be as much as 1 per cent, would flash to steam, therefore any fuel returning to the pressure pump from a ring main or spill return line must be pressurized to a pressure in excess of 20lb. per sq. in. gauge. This involved two-stage pumping and pressure control of the boost pump to maintain a reasonable constant discharge pressure over a range of outputs, since the net boost pump flow equalled the sprayed flow.

With the rotary cup system of atomization, a low particle size of roughly 100μ could be obtained with a viscosity as high as 400 S.R. 1, resulting in low preheating temperatures of about 180 deg. F. Thus two-stage pumping to avoid steam formation at the pump suction was unnecessary. It should be mentioned that steam was not the only reason for trouble being experienced with pump cavitation and vapour locking of the fuel system. Air coming out of solution at the point where the return line joined the pressure pump suction would cause trouble if the pressure were very far below atmospheric, even with an oil temperature of 180 deg. F. However, providing the pump was near the tank and had a small positive head, two-stage pumping was unnecessary with the oil temperature necessary for atomization by the rotary cup principle. Other advantages of the lower oil temperature were the smaller size and lower cost of the heaters and the possibility of using synthetic rubber O-ring seals in fuel system components which, whilst perfectly satisfactory at about 200 deg. F., would be unreliable at temperatures of 260 deg. F. The possibility of using Fluon (P.T.F.E.) at temperatures of 260 deg. F. might be a solution to this problem.

2) The pressure jet burner, with its swirl atomizer, required a high pressure to achieve satisfactory atomization with atomizers of reasonably high flow number. To achieve even, say, a turn-down ratio of 1·4, the minimum atomization pressure would have to be doubled unless a duplex atomizer or spill return system were used.

Whilst these high pressures were no disadvantage for the sprayer itself, they became a distinct disadvantage when one considered the complete fuel system. Automatic control valves, fuel lines, pumps, and at least the last stage heater must be designed for unnecessarily high pressures.

When one considered the spill return system, which was the only system using a swirl atomizer that was capable of a significant turn-down ratio over a continuous range, the problem of high circulating flows arose. It was an unfortunate characteristic of the spill return swirl atomizer that, as the sprayed flow decreased, then at constant inlet pressure the flow to the atomizer increased. At a turn-down ratio of five, the circulating flow was about double the maximum sprayed flow for a constant inlet pressure. This meant that the main pressure pump, or circulating pump, depending upon the system used, must be capable of double the maximum sprayed flow for a 5:1 turn-down ratio. Whilst the difficulties mentioned above were not insuperable, the solution to these problems was expensive for a fully modulating burner with controls for constant air/fuel ratio.

The swirl type atomizer, because of the fine passages inherent in its design, was very sensitive to blockage, and because of this, filtration to a fine particle size was necessary to ensure maintenance of high performance. The rotary cup system had no such fine passages and the only filter necessary was that to protect the pump from damage. This amounted to having two-stage filtration for the swirl atomizer system and only single-stage filtration for the rotary cup system.

For instance, a rotary cup oil burner with a maximum sprayed flow of about 6,000lb. per hr. would have a fuel pressure at entry to the burner of about 15lb. per sq. in. gauge and a temperature of about 180 deg. F. The circulating ring main flow would be designed for only about 10 per cent more than the maximum sprayed flow for all burners connected to the main. This burner would have a turn-down ratio of about 15:1. The authors stated in their paper that the swirl atomizer method of atomization was an obvious choice on the grounds of simplicity. He would agree with them if one considered only the atomizer, but when the whole fuel system was considered, this simplicity vanished and one was confronted with a very complex system. The rotary cup atomizer and primary air fan was probably a little more expensive than the spill return sprayer, but when one compared the whole system for both burners from tanks to atomizers, he thought the rotary cup system would be found to produce the cheaper installation and would be more simple and reliable because of this.

He would like to ask the authors a few detailed questions concerning the equipment described in their paper.

What form of flame failure apparatus did they consider best for watertube boiler applications where several burners were installed? Did they think photoelectric cells could be beamed effectively on the flame of just one burner, or was it necessary to use acoustic or flame ionization methods?

The question of viscosity control was becoming important with large burners with controlled air/fuel ratio. What type of viscosity controller did they consider most suitable?

The register combustion test facility shown in the paper appeared to consist of a 7-ft. diameter tube immersed in a tank of water with sight tubes along its length and should prove very useful for testing and developing burners of that size of combustion chamber. For other sizes of combustion chamber, however, results obtained from this size could only be a guide. Was it possible with this size to change the diameter of the water cooled tube?

Would the authors produce a diagram of the fuel system they would propose for a fully modulating spill return burner with air/fuel ratio control.

Concerning Table III, would the authors give a figure for the necessary $\Delta P/P$ to achieve a heat release rate of $2 \cdot 10^5$ B.t.u./hr./Ft^3/atm. with the "optimum" register.

The section of the paper on the aerodynamics of flame stabilization was most interesting but rather incomplete inasmuch as it said very little about the fluid dynamics of producing flow reversals with the systems discussed. Would the authors discuss more fully the fluid dynamics of the register with the concentric conical baffles? This Lucas register was very similar to the Sulzer design described in the "Sulzer Technical Review", 2/1957, which had a conical baffle but with annular slots. With the Lucas concentric conical baffle register it would appear that the overlapping of these baffles would produce a toroidal vortex at each overlapping cone and by rather critical setting these vortices could be arranged to coincide to produce one large vortex. Presumably this would allow diffusion of the secondary air to a position behind the vortex rather than diffusing radially outwards from the secondary annulus. He would like the authors' comments on this. Fig. 25 did show a marked degree of radially inward flow of the air issuing from the secondary air annulus.

Authors' Reply

The authors were grateful to Commander Lake for his remarks, which put into perspective the relationship between their firm and the Admiralty dating from the years of the last world war. They wished to pay tribute to the most fruitful collaboration with the engineering staff at Haslar who had so well directed this very successful team work.

The authors wished to thank Mr. Sampson particularly for the part he had played in the initiation of the paper and for drawing attention to the importance of the relationship between particle size and burning time as indicated in Figs. 16 and 17. It should be mentioned that the curves shown for the combustion time of carbon particles are derived from the following formula due to Vulis (reference 2 of the paper):—

$$t = \frac{\rho_f \, d \, (O/F)}{2M_{og} \, \rho_g} \left\{ \frac{1}{K} + \frac{d}{4D}\left(1 - 0{\cdot}08 \, (d \, V/v_g)^{0{\cdot}4} \right) \right\}$$

where d = droplet diameter

D = molecular diffusivity

K = chemical reactivity of the fuel surface

M_{og} = oxygen concentration in air by weight

O/F = stoichiometric oxygen/fuel ratio by weight

V = particle velocity

v_g = kinematic viscosity of gas

ρ_f = fuel density

ρ_g = gas density

With regard to the reverse flow region for flame piloting downstream of various types of register arrangement, the authors wished to make it clear in reply to Commander Ricks that the best pattern in their view was a vigorous toroidal vortex, as far as possible free from random fluctuations, and that they had found that this was more effectually produced by the arrangement shown in Fig. 25 than by that shown in Fig. 24. The result was that the former arrangement was better able to meet the most stringent demands of high turn-down conditions, although, as was well known, the latter arrangement had proved adequate for several very important applications.

As mentioned at the top of page 149, and as pointed out by Commander Ricks, certain arrangements with a swirler alone apparently fail to produce a reverse flow region, but as pointed out on page 145, the swirler arrangement could be made to produce such a region, even though the details might leave something to be desired.

It should be mentioned in fairness that the arrangement with concentric conical baffles also needed careful attention to detail design if the best results were to be achieved, and that, as found by Commander Ricks, mere size of the vortex was by no means the only criterion.

His 430lb. per hr. at 0·5-in. w.g. as compared with the authors' 250lb. per hr. at 6-in. w.g. might be due to a number of possible differences such as a different flame volume allowable, or a different CO_2 achieved, and it was not possible to comment further in the absence of fuller particulars of the performance and the arrangement.

The authors agreed with Mr. Poulston that droplets were very much aware of Osborne Reynolds, but believed that towards the end of their lives, they developed more than a nodding acquaintance with Mr. Stokes. Mr. Poulston quoted an impressively wide range of drag coefficients, but the authors believed that some of these depended upon the liquid droplet being able to alter its shape under the influence of external forces, and would therefore be invalid for very small droplets. They definitely favoured the use of the solid sphere drag coefficient for simplicity since there were several camels to be swallowed in any case, such as the distribution of primary combustion zone gas composition, temperature and velocity.

The rotary cup atomizer shown in Fig. 10 was indeed used in that flow regime in which the droplets spun off the lip with a uniform size, as Mr. Poulston suggested, and the authors were quite prepared to believe that commercial rotary cup atomizers for registers operated in the "flooded" regime, in which they would act as little more than a fuel distributor, while the air flow over the lip would be the atomizing agent.

The authors agreed most strongly that the ideal distribution of droplet size for combustion was not uniform size, and that the smaller and larger droplets had their individual functions to perform, provided they were present in reasonable proportions. On the whole, it appeared that the type of distribution given by a swirl atomizer was, for all practical purposes, an optimum.

The removal of ash producing elements from the fuel was included in the list on page 146 of the paper simply because it was one of the measures which would obviously result in diminished corrosion. It was not intended to imply that this measure could necessarily be justified economically.

The authors were grateful to Commander Wood for putting into focus the important factors to be noted in designing boiler equipment from the point of view of what the user required, and particularly for stressing that all the equipment provided must be "crew proof". With regard to the crew proofing of pressure jet atomizers, the authors took the view that this was best accomplished by discouraging the dismantling of atomizer components, and treating the atomizer assembly as a single replacement part.

The authors thanked Mr. Kemp for filling in some historical gaps with regard to the early designs of register. They considered that the description of the register illustrated in Fig. 55 formed a most valuable addition to the paper, though its turn-down capabilities and flame dimensions or combustion intensity would also have been of interest.

The information which Mr. Kemp gave on rotary cup burner installations was of great interest. The authors were obviously more familiar with the pressure jet type of atomizer for register work, and it was for this reason that such a large fraction of the paper had been devoted to this type. They could not, however, agree altogether with Mr. Kemp's remarks about the liability of this type of atomizer to maltreatment and faulty assembly as compared with the rotary cup type. The pressure jet atomizers did not contain moving parts and it was quite practical to use them as replaceable sealed assemblies.

The authors admitted that the reference to the effect of steam on the kinetics of the combustion reaction left a great deal unsaid. It was possible to achieve higher combustion intensities without steam than when this was used for the atomization process, but when it was not ncessary to reach the ultimate in heat release, it was perfectly admissible to use steam, providing due allowance was made for the change in flame dimensions and the reduction in flame temperature. The rate of heat transfer by radiation from the flame was thus reduced, but might be offset, in some cases, by the fact that the heat transfer by convection might be raised due to the increased thermal conductivity due to the steam content.

It was indeed gratifying to the authors to see that such admirable progress had been made in the art of heavy fuel combustion as that illustrated by Mr. Eskdale's achievements. It was to be hoped that a paper would be forthcoming giving fuller particulars of this work.

Replying to Mr. Hutchings, it was appreciated that increased air pressure loss would mean an increase in the power consumption of the fans, but it had always been the object of the authors to achieve the required performance with the bare minimum of pressure loss, and if pressure losses were rising, this was only the inevitable outcome of increasingly stringent demands on the combustion system in terms of combustion intensities required. There would be an economic optimization problem to be solved in these cases.

With regard to the use of spinning cup burners for large outputs such as 2,500 or 3,000lb. per hr., several of the other contributors had made valuable remarks based on a wider experience of this particular field than the authors could claim.

The use of steam as an atomizing agent had been dealt with more fully in the reply to Mr. Kemp's remarks above.

With regard to Fig. 18, which showed the rate of carbon deposition as dependent on chemical composition of the fuel, the authors wished to make it quite clear that this experiment related to the building up of carbon on a special metallic receiving plate inserted into the primary combustion zone of a combustor, and that the object had been to compare the carbon forming tendencies of different fuels, and not to arrive at any absolute values of carbon formation rate.

With regard to the fitting of more than one register on the same boiler front, the authors had had experience of cases in which flow anomalies had occurred in the common header. The convergence of the flow from the main volume of the header towards certain registers had given a free vortex effect analogous to the swirl which sometimes occurred when liquid was drained from a tank through a small orifice. This had caused considerable reductions of the discharge coefficient of the registers concerned, and since the occurrence of this phenomenon was largely dependent upon the geometrical configuration of the header ducting, it occurred in some designs and not in others. This might have been the explanation of the conflicting evidence to which Mr. Hutchings referred.

In reply to Lieutenant Commander Humby's remarks on the flow patterns employed for the stabilization of flames, the authors wished to emphasize the difference between the reverse flow regions produced by the arrangements of Figs. 24 and 25 as already set out in the reply to Commander Ricks. It was not claimed that either pattern was exclusive to Lucas designs, but each was perfectly satisfactory in appropriate applications.

The authors were particularly grateful to Lieutenant Commander Humby for pointing out the importance of designing the register and boiler in conjunction with one another. They were well aware from actual experience of the possibility of encountering flame pulsation trouble if due attention were not paid to this aspect, and were conscious of the importance of the choice of sprayer cone angle from this point of view.

The authors were grateful to Commander Cooper for throwing into perspective the present position with regard to the heavy oils being supplied by the oil companies, and the trend towards still heavier oils.

As mentioned by several other contributors to the discussion, there were a great many applications in which a very modest degree of turn-down was all that was required; perhaps only 1·5:1. Where a high turn-down was required, however, it was quite true that the air flow had to be turned down also, but this would only be associated with the very large variations of applied air pressure mentioned by Commander Cooper if the register were of fixed effective area. It was for this reason that many registers were provided with variable area passages such as those shown in Figs. 33 and 34 in the form of longitudinal slots which could be blanked off to an adjustable extent. In this way, it was possible for the air pressure range to be much smaller than the square of the turn-down range.

With regard to steam atomizers, the authors felt that the position was as mentioned above in the reply to Mr. Kemp. However, when using duplex or spill atomizers, even the highest required turn-down could be obtained without having recourse to steam as an atomizing medium.

Regarding the control of air/fuel ratio over a wide range, the authors had the benefit of many years of experience in the aircraft gas turbine field where maximum/minimum fuel flow ratios sometimes greatly exceeded anything that could possibly be required in register practice. Such wide range air/fuel ratio controls could satisfactorily take into account any of the factors which could tend to cause variations of the air/fuel ratio.

The authors were in full agreement with Mr. Pritchard regarding the steps to be taken in the storage of heavy oil to secure freedom from water content as far as possible, but were very conscious of the fact that this was only half the story, and that for one reason and another a much higher water content could often be found in the oil actually in use on board ship.

As a result, the precautions he mentioned for preventing steam and vapour formation at the fuel pump inlet were quite necessary.

While carbon was perhaps the chief stack solid usually encountered, and it was certainly possible to do something about this in the register design, the authors wished to point out that ash formation was in quite a different category, and in this respect they were at the mercy of the composition of the particular fuel in use.

The authors admitted (in reply to Commander Cooper's written comments) that much of the paper was phrased from the point of view of people who had spent the major portion of their effort on aircraft gas turbine combustion. The reference to a long flame at the top of page 139 was, of course, an example of this, since all register flames are long compared with those used in aero-gas turbine practice. The authors apologized for any misunderstandings which might have arisen from this source.

The authors would not agree entirely with Commander Cooper's statement that the finest possible atomization was required and that this meant a wide cone angle. On the one hand, as already mentioned in the reply to Mr. Poulston above, atomization could be too fine, which hindered the mixing of the fuel and air, and on the other hand, the quality of the atomization was not tied up with the spray cone angle in precisely the way suggested by Commander Cooper.

It might well be that some of the simplex atomizers on the market at the present time showed smaller droplet sizes for larger spray cone angles, but the simplex atomizers manufactured by the authors' company did give an S.M.D. which was sensibly independent of spray cone angle, and which was, moreover, outstandingly fine compared with some others, as shown by the formula quoted on page 138.

The authors were of course well aware of the work of Sir Geoffrey Taylor and Dr. Watson, and regretted not having made specific mention of it.

Further remarks on the operation of rotary cup atomizers and steam-assisted atomizers were to be found above in the replies to Mr. Poulston and Mr. Kemp respectively.

The pilot registers illustrated in Figs. 33 and 34 utilized a draught loss which varied as stated over a range from 24-in. w.g. at the full load condition to 1-in. w.g. at the turn-down condition. This was made possible by the operation of the louvres, whose position could be adjusted to maintain an approximately constant air flow through the register, the fuel flow being also constant. Since the function of these registers was to act, as it were, as a candle, it was not necessary for a very high standard of performance to be obtained.

With regard to the type of duplex atomizer shown in Fig. 13, this was familiar in aircraft practice, in which field the practical manufacturing problems had been solved, and as mentioned elsewhere, if details of the installation demanded its use, it could be a replacement item if it were considered that the cleaning operation in the boiler room would involve too great a risk of mechanical damage.

Where a serious problem of air turn-down existed, such as that mentioned by Commander Cooper, it was the recommendation of the authors that the type of design shown in Figs. 25, 31 and 32 should be given serious consideration, since it entirely solved the problem of having to cope with the excessively small pressure drops which he mentioned.

The authors did not find that the quality of combustion was any better at an atomizing pressure of 1,000lb. per sq. in. than at 600lb. per sq. in. The reason for using 1,000lb. per sq. in. in certain cases was to avoid the atomizing pressure dropping too low under turn-down conditions, especially when using simplex atomizers.

Flow distributors were recommended by the authors, particularly for duplex sprayers of the type in which a common swirl chamber was used for both pilot and main flows (duplex I). In this case, however consistently the atomizers were manufactured, there was a tendency towards instability of flow distribution as between different atomizers in parallel. This could be overcome by the use of a distributor in the manner described, and had the further advantages that it could take the form of a combined distributor and throttle valve, and would enable a continuous check to be kept upon the performances of the individual atomizers and their pilots. There was no corresponding advantage to be gained by applying distributors to spill type systems.

With regard to the heat release of 10^6 B.t.u./ft.^{3}/hr. mentioned, this was quoted as a maximum practicable figure. The Admiralty registers referred to had been run, as far as the authors were aware, at up to $0 \cdot 75 \times 10^6$ B.t.u./ft.^{3}/hr., and 10^6 B.t.u./ft.^{3}/hr., had been obtained on an experimental register tested within the authors' Company but not introduced into service.

Mr. Darling was not correct in deducing from Figs. 16 and 17 that a change over from bunker fuel to gas oil in a given combustion chamber would result in a diminution of flame volume. The situation was rather that if such a change over were made, the register could be designed to give a shorter flame. In the absence of any change to the register design, the flame would probably be equally long, as found by Mr. Darling.

Since the flame length was virtually determined by the register design, this explained and confirmed Mr. Darling's remarks on the experience at Pametrada in running with a range of different fuels.

The carbon deposition tests described by the authors on page 142 had already been commented on in the reply to Mr. Hutchings above. These tests were of course on aircraft fuels, or fuels proposed for aircraft use, but they did establish the effect of aromatic content on the tendency to carbon deposition. As pointed out elsewhere, the results did not suggest that a film of air could be used in practice to prevent carbon deposition, but only to reduce the rate of deposition.

With regard to the interpretation of Fig. 20, it should be remembered that the velocities quoted were only the component perpendicular to the air film, and it was doubtful whether a value as high as 100ft. per sec. would be met with except possibly in a heavily loaded aircraft chamber. It was admitted of course that the film of air in these circumstances was of very much greater use as a cooling device than as a means of protection against carbon build-up.

The authors admitted that the combustor was often not the best solution for a given boiler. The economic considerations mentioned by Mr. Darling would have to be taken into account, but the fact remained that substantially higher heat releases could be obtained than in a register, together with better stability and control characteristics. The best applications of combustors were probably those in which the whole boiler installation had been designed with a view to the employment of a combustor.

The importance of using a flow distributor in certain cases had already been dealt with above in the reply to Commander Cooper's written comments.

In reply to Mr. Gray, Fig. 9 in the paper had been drawn for a value of viscosity typical of certain aircraft fuels and showed the trend of dependence of S.M.D. upon flow number and pressure. For actual figures relevant to a given case, it was of course necessary to redraw it for the appropriate viscosity, which would be quite an easy matter. Alternatively, one could work direct from the formula quoted.

The droplet sizes given had been measured in the authors' company and elsewhere by two methods. In one, the sprayer was supplied with an appropriate wax heated to a temperature at which its surface tension and viscosity were equal to that of the fuel, the resulting spray being solidified and examined, while in the other method, the droplets were allowed to impinge on to a magnesium oxide film where they left impressions which could be studied and interpreted.

The measurements had been carried out over quite a substantial range, although a certain amount of extrapolation had been done. The authors did not believe, however, that the relative probability of collisions was increased at the higher flow numbers.

Mr. Gray's remarks on spinning cup atomization and steam atomization had been dealt with in previous replies. Likewise, the position regarding Fig. 18 had also been clarified.

The authors' opinions on the method of flame stabilization shown in Fig. 24, for example, had been given above in the reply to Commander Ricks.

Mr. Gray's remarks on Table III had been dealt with in the reply to Commander Cooper's written comments.

With regard to the correlation of ΔP against combustion intensity, the authors desired to point out that there were two types of this correlation. In one method, the correlation was obtained by running the same register at different throughput conditions, but in the other type, which was of greater interest and importance, the design was varied with the combustion intensity to give the least pressure drop at which that intensity could satisfactorily be realized. Within the authors' experience, the power 0·5 fitted better than 0·75. Mr. Gray's figure of

TABLE IV.—TABLE OF REGISTER PERFORMANCE

	Register diameter, in.	Fuel flow, lb./hr.	Flame length, ft.	Flame diameter, ft.	Combustion intensity, M.B.t.u./ hr. ft.^{3}	Forced draught,		Atomizing pressure, lb. per sq. in.	Atomizer flow number	S.M.D., micron
						In. w.g.	Percentage			
Full load	15	1,875	7	4	0·38	5·9	1·45	500	9·3	111
Turn-down		1,400	8	4½	0·20	3·3	0·81	275	9·3	138
Full load	10	900	6	3	0·382	5·9	1·45	500	4·5	97
Turn-down		675	6	3½	0·21	3·3	0·81	275	4·5	118

Fuel—950 to 3,500 seconds oil, preheated to a viscosity of 15 c.s.
Atomizers—simplex (Demon III)
Air/fuel ratio—16·8 (nominal)

45-in. w.g. did seem a little on the high side, and the authors felt that 35-in. w.g. would be nearer the mark and it might be possible to reduce even this.

The register performance quoted on page 150 resulted in the attainment of an overall thermal efficiency of 85 per cent, and was declared in 1953 by representatives of the boiler maker concerned to be well in advance of contemporary practice.

With regard to the justification of cost, the high pressure fuel pumps, spill systems and high air pressures were the authors' solutions to certain technical problems which were not present in every application. If these items were too costly, the answer might be to change over to a boiler specification which might be of a more conventional nature, and might not offer these problems.

Mr. Lawrie had given an example of the performance of a certain register burning 3,500 seconds fuel, and it was interesting to quote for comparison Table IV giving the performance of a register similar to that shown in Fig. 24 of the paper:—

In his discussion of the performance of a hypothetical register using a 8:1 turn-down ratio, Mr. Lawrie had made out what was, in effect, a very strong case for a variable register such as that shown, for example, in Fig. 25. This would avoid the necessity for installing a high powered fan to deliver 32-in. w.g.

The authors admitted, in reply to Commander Sidgwick, that one view which could be taken of the atomization process as exemplified by the pressure jet atomizer was that once the fuel was distributed into a thin conical film, surface tension would do the rest. However, it should be remembered that variation of the surface tension over quite a wide range, for a given viscosity, pressure and flow number, might lead to practically no change of S.M.D., even though the details of the atomization process might be altered. This mechanism had been studied in great detail by Mr. R. P. Fraser, and the authors would like to acknowledge here his most valuable work.

Commander Sidgwick had stated that the size distribution in a spray depended on a large number of different factors, but it had been the authors' experience that with pressure jet atomizers there was singularly little change in the shape of the size distribution curve, and that the complete particulars of the size distribution were therefore expressible in terms of a single parameter giving the mean droplet size. This was the S.M.D., as already pointed out, and once formulæ were found for this in terms of the various independent variables, further research into the mechanism of the atomization was only of secondary interest to the combustion engineer.

Commander Sidgwick was quite correct in pointing out that the fuel droplets were launched along generators of what was, for all practical purposes, a cone, and it was for this reason that when using a pressure jet swirl atomizer, it was of no significance whether the sense of rotation in the swirl chamber was right handed or left handed.

The authors were glad that Mr. Wells had emphasized the importance of the choice of oil preheat temperature, not only in relation to the type of fuel atomizing system to be chosen, but also in relation to O-ring seals. They had had considerable experience of high temperature seals of this type in aircraft fuel system work, where, particularly with high flight Mach No. conditions, and with spill systems, it had become necessary to cater for higher fuel temperatures than would ever be met in register work. They felt that, resulting from this work, the oil seal problem had been solved for all practical purposes.

With regard to the high fuel pressures mentioned by Mr. Wells, the authors agreed that these must be taken into account in their effect on the design of valves, lines, etc., but felt that he had probably exaggerated the seriousness of the problem. The trend towards heavier fuels and increased heat releases would probably lead automatically towards higher fuel pressures in the future, in any case.

As regards filtration, the authors felt that with the exception of the pilot flow passages of duplex atomizers, the general tendency was for the atomizers to require no higher degree of filtration than that required in any case by the pump.

With regard to flame failure apparatus, the authors felt that acoustic methods were unsatisfactory, and that the best method would probably be the lead sulphide cell or the ionization probe.

Proprietary viscometers were now available which could be arranged to relay their readings to the oil heaters, and thus enable an automatic adjustment of the oil temperature to take place, giving a preset constant fuel viscosity at the sprayer.

The authors stated that, in addition to the fire tube diameter mentioned in the text, in the register testing installation in their Company, other fire tube diameters would also be available, which, together with actual experience in boiler installations, would enable a complete assessment of the effect of fire tube size on flame characteristics to be made.

With regard to the fuel system for the spill return burner with air/fuel ratio control, the details of this would depend on the exact requirements, and the authors would be happy to make proposals for any specific case.

In Table III the authors felt that the heat release of 2×10^5 B.t.u./hr./ft.^{3}/atm. would probably require about 1-in. w.g., or 0·25 per cent $\Delta P/P$ if the whole of the air had to be introduced at this pressure, though the bulk of it could probably be supplied at a lower pressure if a certain fraction were supplied as a preheated forced draught.

The concentric conical baffle type of register did not show any particular tendency to form separate toroidal vortices associated with the individual baffle gaps, as all the separate streams of air invariably merged together to produce one composite flow pattern, but it was indeed necessary to pay careful attention to the settings of the trailing edges of the cones in order to obtain the vortex proportions and participation of the secondary air as shown in Fig. 25.

Following this detailed reply to points raised by contributors to the discussion, the authors wished to mention that the suggestion was made some two to three years ago at a meeting of the West Midlands Section of the Institute that they should write this paper, and they did this at the request of the Council to set out the principles which had been adopted by their Company and employed over the years for gas turbine combustion. They had had the good fortune to be approached in connexion with the combustion system for the Whittle engine in 1940, and also by the Admiralty during and after the last war in order to apply the same principles which they had evolved to the marine firing problem. They therefore owed a debt of gratitude to the Admiralty staff at Bath and Haslar which they had not already sufficiently acknowledged. It was due to the encouragement and co-operation of these good people that they had had the opportunity to apply in the marine field the principles which they had evolved in the aircraft field.

These circumstances explained why there was possibly only scant experimental data in the paper on the combustion of the heaviest oils, and why so much emphasis had been placed on the application of principles drawn from gas turbine combustion experience. It was inevitable in these circumstances that much criticism should be met from those who felt that the authors had not adequately covered the wide field of residual oil combustion in practice, and, in this connexion, it was understood that something like ten million tons of crude oil had been burned in industry in 1958, and 4¼ million tons in world shipping. It was hoped that the above remarks went some way towards explaining and excusing this situation.

Another major criticism centred around the use by the authors of the expression "stabilized flame principle" in connexion with the use of the toroidal vortex as a vehicle for flame stabilization in certain designs. The authors obviously could not claim any monopoly in the toroidal vortex, but they did feel that there was some justification for the remarks they had made, in view of the extremely large amount of original work which they had done personally in the scientific investigation of its flame stabilizing properties and in its application to practical combustion design.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at the Memorial Building on Tuesday, 27th January 1959

An Ordinary Meeting was held by the Institute on Tuesday, 27th January 1959 at 5.30 p.m., when a paper entitled "Heavy Oil Burning" by J. S. Clarke, O.B.E., Ph.D. (Member) and G. J. Hudson, M.A., was presented and discussed. Mr. R. Munton, B.Sc. (Chairman of Council) was in the Chair and 169 members and visitors were present. Eleven speakers took part in the discussion which followed.

A vote of thanks to the authors, proposed by the Chairman, was accorded by acclamation. The meeting ended at 7.55 p.m.

Section Meetings

Bombay

A boat cruise round Bombay harbour in moonlight, arranged for the benefit of the registered members of the Section and their guests, was held on Friday, 20th March 1959. The s.l. *Begum,* owned by Mazagon Dock (Private), Ltd., was made available free of cost through the good offices of Mr. G. E. Kerr (Local Vice-President). Members with their wives and guests, 110 in all, took part in the cruise and shared a buffet dinner and the programme of entertainment which had been arranged on board. The cruise lasted from 7.0 to 11.0 p.m.

Captain T. B. Bose (Chairman of the Section) thanked Mr. Kerr and the members of the Committee who had assisted in making the outing a success.

North East Coast

A very successful visit to the United Kingdom Atomic Energy Authority Power Station at Chapel Cross (near Annan) was held by the North East Coast Section on Saturday, 11th April 1959. The guides and power station staff were most co-operative and helpful and the visit was both enjoyable and instructive and was felt to be a Saturday well spent by those fortunate enough to be able to take part.

Singapore

By kind permission of the Principal, Mr. D. J. Williams, M.A., B.Sc., in co-operation with the Chairman of the Singapore Section, Mr. F. Helm, a very enjoyable visit to the Singapore Polytechnic was made on Saturday, 7th March 1959.

A party of forty, which included members of the Section and their ladies and friends, assembled at 3.30 p.m. in the foyer of the Polytechnic. They were first shown a film which followed the progress of the building of the Polytechnic and on which a commentary was provided by Mr. C. I. C. Scollay, B.Sc., B.E., Head of the Engineering Section. Four groups were then formed and were taken charge of by Messrs. Tan Peng Nam, K. D. Drysdale, F. Helm and G. A. Baker. Visits were paid to every department of the Polytechnic, including the Departments of General Education, Science and Technology, Engineering, Building and Architecture, Commerce, and the Nautical Section. The various workshops and stores were also visited.

When the tour had been completed the various groups met again in the canteen where a delightful tea had been prepared. There, Mr. S. A. Anderson (Local Vice-President) addressed the party, and on behalf of the Section thanked Mr. Williams and his colleagues for not only making the visit possible but also successful.

Victorian

The Victorian Section Committee for 1959 is constituted as follows:

Chairman: A. J. Edwards (Local Vice-President)
Committee: C. Bie
P. Bossen
J. E. North
G. Seales
Lieut.(E) D. W. K. Vagg, R.A.N.
J. B. Thomson
Honorary Secretary: K. Paxton
Honorary Treasurer: J. H. Coles

West Midlands

At a meeting held at the Birmingham Exchange and Engineering Centre on Thursday, 9th April 1959, Dr. J. S. Clarke, O.B.E. (Member) and Mr. G. J. Hudson, M.A., presented an illustrated lecture entitled "Heavy Oil Burning". Mr. R. S. Robinson, B.Sc. (Chairman) was in the Chair and the meeting was attended by fifty-six members and visitors.

Dr. Clarke outlined the prime factors which had to be taken into consideration in the design and development of heavy oil burner systems. These systems were clearly illustrated by the numerous slides which were then shown. By means of two 16-mm. silent films taken with high speed cameras, Dr. Clarke showed the actual burning of the fuel inside the combustion chambers. The slow motion action of these films enabled the flame pattern and the effect of varying the air supply to be studied in detail. Mr. Hudson joined Dr. Clarke in answering the questions put by eleven members in the discussion which followed.

The Chairman expressed on behalf of the Section their appreciation of, and indebtedness to, Dr. Clarke and Mr. Hudson for an exceptionally interesting lecture. The meeting was closed at 9.0 p.m.

Election of Members

Elected on 11th May 1959

MEMBERS

Walter Danby
William Graham
Henry Ernest Brooke Gratte
Gordon Arthur Grout
Yasumatsu Hamada
George Handley
John Arthur Edward Heard, B.Sc.(Eng.) London
Robert Andrew Loraine
Robert William McGuiness
Minoru Murata
Richard Reid
Philip Robert Salisbury, B.Sc. (Naval Arch.)
Frank Cyril Alexander Street, M.B.E.
Cyril Louis George Utton, Lieut. Cdr., R.N.(ret.)
Joseph Alexander Wandless
Harold Westoll

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Dilip Kumar Auditto
George Lorenz Bartholomeusz

Anthony Billis
Harry Bernard Burnett
Charles Cowe
Stephen Raymond Davies
Ronald McPherson Davis
Thomas Goudie
Robert Gilmore Greenow
William Monahan Jack
Hareesh Gopal Jhingran
Alan Charles Jones
Shrinivas Raghunath Khare
Alan John Lewis
Robert Parker Mackay
Ram Sarup Nayar
Arthur Shaw
Douglas Hope Walsh

ASSOCIATES

Sardar Taffil Uddin Ahmad
John Goddard Coverdale
Albert John Ficken
Frederick Douglas Jones
Ahmed Nawaz
Mounir Saba

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John Frederick Brazier
John Richard Chambers
James Dennis
Peter James Foster
Malcolm James Fox
Fred Haigh
James Norman Morris Maas, M.A.(Cantab.)
George Cowie Mack
Stanley Keith Metcalf
Jemi Pirojshaw Mistry
John Terence Peters
Derek Rhoden
John Anthony Vost

STUDENTS

Richard Leonard William Boorman
Montague Ian Campbell
Edward Arthur Childs
Michael William Hosking
Peter Douglas Meredith
John Papadimitriou
Andrew John Robinson
Terence Richard Smith
Valadi Vaidyanathan Viswanathan
David James Williams

PROBATIONER STUDENTS

Robert Graham Coates
Alan David Curzon
Thomas Anthony Edwards
James Robert Jennings
Stuart Hugh McMillan

TRANSFER FROM ASSOCIATE TO MEMBER

Dennis Dawson
Laurence James Prandolini

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER

Robert James Ashton
Thomas William Noble

TRANSFER FROM GRADUATE TO ASSOCIATE MEMBER

Peter Leck
Patrick Daniel Fleming
Cyril John Flynn
Frank Henry Muller
John William Reay
William Edward Sedgwick
George Alfred Toes

TRANSFER FROM STUDENT TO GRADUATE

Neil Denton Nimmo

TRANSFER FROM STUDENT TO ASSOCIATE MEMBER

Richard George Lukes

TRANSFER FROM PROBATIONER STUDENT TO STUDENT

Francis Devitt
Michael Risbey