EXPERIENCE WITH DISTILLATE FUEL IN STEAM-DRIVEN WARSHIPS

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Synopsis

Although conventional steam generation will remain in R.N. service for perhaps three decades, innovation is past. Starting from the change to liquid fuel, this article traces the history of oil-fired naval boilers up to the mid 1960's. At that point the adoption of all-distillate fuel became imperative. The main part of the article covers the last fifteen years' operational experience, successful in terms of the predicted benefits but imposing a tauter operating discipline, costly to acquire, and exposing the marginal nature of certain aspects of current boiler design. More recent developments described include steam atomization in R.N. service.

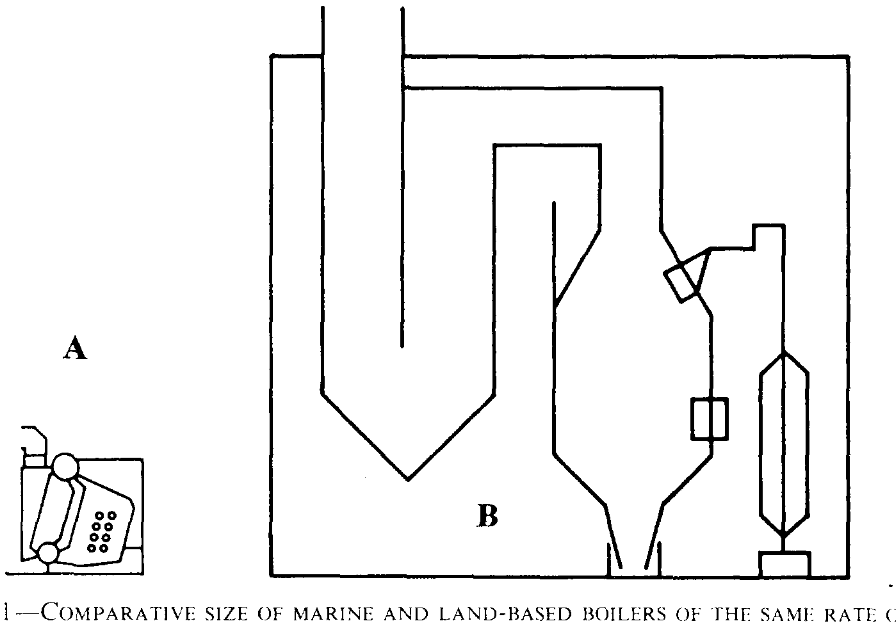

FIG. 1—COMPARATIVE SIZE OF MARINE AND LAND-BASED BOILERS OF THE SAME RATE OF EVAPORATION
(A) OIL-FIRED MARINE BOILER (B) PULVERIZED-FUEL-FIRED LAND-BASED BOILER

Introduction

Background 1913–1959

Sixty odd years ago the Royal Navy changed its principal boiler fuel from coal to oil. The reasons which prompted this action were twofold:

(*a*) Oil would provide the margin of speed necessary to dominate a comparably-armed but coal-fired adversary.

(*b*) Its higher calorific value and conformability to any storage space conferred an increase in endurance of the order of 40 per cent.; the ability to replenish at sea, a potential increase on task of 25 per cent.

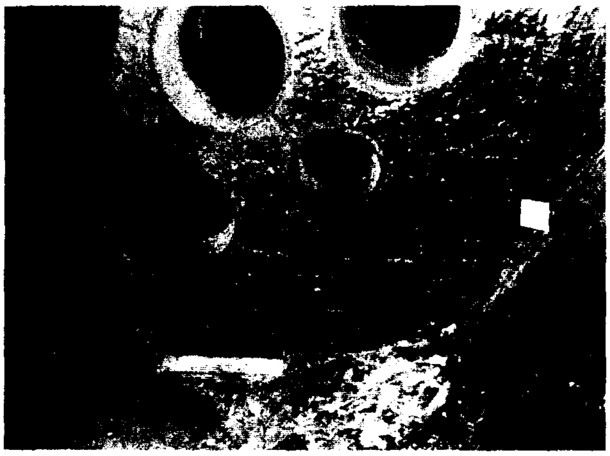

FIG. 2—TYPICAL FRIGATE BOILER FURNACE AFTER 1000 HOURS BURNING FFO (FRONT WALL)

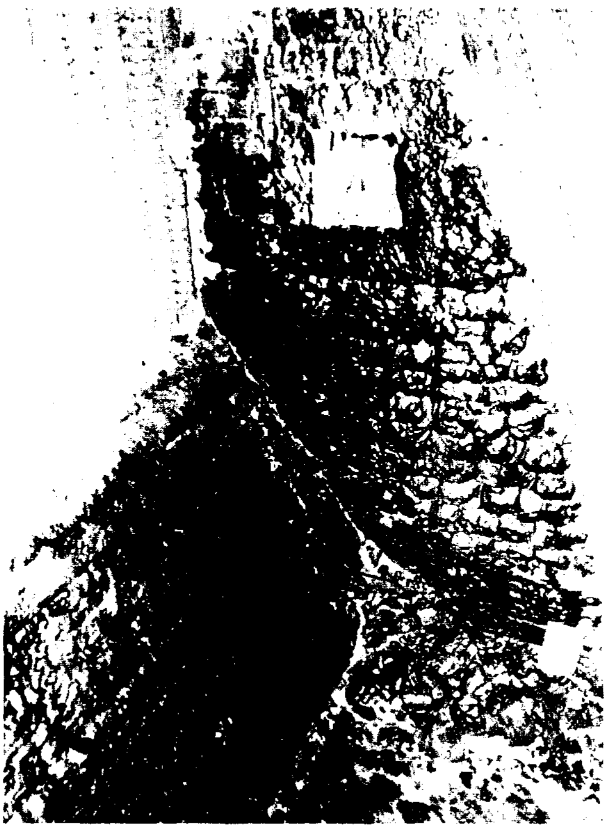

FIG. 3—TYPICAL FRIGATE BOILER FURNACE AFTER 1000 HOURS BURNING FFO (BACK WALL)

In the struggle which followed, the constraints of the principal (North Sea) arena denied in practice the full advantages that this bold step achieved in theory.

From 1913 until the Second World War, the predominant source of naval fuel was the Persian Gulf where the nature of the crude combined with Britain's privileged trading position to produce a high-quality fuel at a rock-bottom price. Boiler designers naturally took advantage of the latitude this high quality permitted and the gypsy's warning of the 1913 Royal Commission on this very point went unheeded. This policy came home to roost with the closure of the Mediterranean route in 1941. The resultant swing to western fuels and the soaring demand for middle distillates had immediate and sobering consequences in terms of boiler cleanliness and brickwork life.

After the war, it soon became apparent that the hard facts of supply and demand precluded any return to the *status quo ante*. Indeed the forecast demand for distillates was so alarming that, far from seriously considering them as boiler fuel, the trend was towards expanding the utilization of low grade fuels, not excluding peat. Nonetheless an Admiralty paper of 1949 did in passing make brief but prophetic mention of the risk of explosion were gas oil to be burned under boilers. From this background a new boiler fuel specification was evolved and the initials FFO (Furnace Fuel Oil) became common currency. The new problems of multi-source purchasing, incompatibility, and instability were recognized and a considerable research programme inaugurated which was to lead, via the arcane subject of pumpability tests, to the chemistry of vanadium compounds a decade later. Boiler cleaning methods likewise evolved with conventional water-washing, chemical cleaning and high-pressure water jetting employed to cure that which it seemed could not be prevented.

Over the same period, the increasing sophistication of warship weaponry and communications was demanding an exponential increase in electric power and intensifying as never before the pressure to reduce propulsion machinery weight and, particularly, volume (FIG. 1). The appearance of the single-furnace controlled-superheat boiler was immaculately on cue. Heat release rates around 56×10^4 Btu/h/ft^3 of furnace volume (1) were more than double that of the conventional Admiralty 3-drum design and nearly four times contemporary Merchant Navy practice. It soon became apparent however that this had been achieved at the expense of a fireside fouling problem of a magnitude quite incompatible with the high usage demanded of the post-war Fleet. (FIGS. 2 and 3).

The Problem with Residual Fuels

The heavy fouling experienced in these high-firing-rate (HFR) boilers not only damaged brickwork, but reduced heat transfer and, in extreme cases, caused superheater failures. It was also found to be substantially insoluble in water. In a five-year period in the early 60's twelve ships required premature generator tube renewal to remove deposits, to renew superheater tubes or to make good other damage attributable to FFO burning. The precise nature of this fouling is described by Brown and Ritchie (2). The morale of ships' engineering personnel wilted under the relentless, repetitive cleaning and repair task which had paradoxically increased as design 'improved'.

The Search for a Solution

A working party was set up in 1964 to consider the problem and recommend a solution. Three practical possibilities were examined:

(*a*) Treatment of FFO in ships.

(*b*) The use of an alternative refinery-treated residual oil.

(*c*) The use of a wholly distillate fuel.

Treatment of FFO in Ships

The treatments available were of two types: chemical—by the use of additives, and mechanical—by centrifuging. Many chemical treatments had been investigated, on both sides of the Atlantic, but few showed any real promise. Those that did offered, as an alternative to hard slag, larger quantities of soft deposits. This would not necessarily be an advantage as the rate of deposition in parts of the furnace not reached by the sootblowers might be so rapid as to make the constraints worse than before.

The efficacy of centrifuging out the harmful constituents of FFO was extremely doubtful, though technically just possible. Even if centrifuging could have been shown to be effective, however, the space for large centrifuges and for storage of the separated residue was just not available within existing warships.

Thus, although fuel treatment had met with some success in other applications, the high forcing rates of naval boilers and the severe space restrictions in warships precluded its use in the Royal Navy.

Alternative Residual Fuels

The harmful impurities, sulphur and vanadium, can be removed by refinery processes. These processes, however, are uneconomic and were not carried out on a commercial basis. This measure would have committed the Royal Navy to an expensive 'special' fuel not obtainable world wide and was quickly eliminated.

Distillate Fuels

The choice had now narrowed down to selecting a suitable distillate fuel. Three were examined:

(*a*) Marine Diesel Fuel.
(*b*) High Flash Point Aviation Kerosine (AVCAT).
(*c*) Naval Diesel Fuel (DIESO) a wholly distillate fuel (Gas Oil).

At this stage, consideration was given to R.N. fuel requirements other than for boilers. All major warships carried some high-speed diesel engines, and marine gas turbines had appeared in the Fleet. These engines were not designed to run on marine diesel fuel but would run on the other two. AVCAT is expensive and not readily available in all parts of the world. DIESO, however, was already carried in ships for diesel and gas turbine engines and was readily available. In addition to being an eminently suitable fuel to solve the boiler problem, it had the advantage that ships with mixed propulsion plants—steam and gas turbine—could become single fuel ships. This would confer important advantages both operationally and in the flexibility of use of the machinery, with attendant simplification of fuel systems and fuelling. Although DIESO was somewhat more expensive than FFO, it was considered that the extra cost was more than justified by the benefits to be gained. Trials which were being carried out in four ships, burning DIESO exclusively, were showing that the optimism felt about this fuel, as a solution to the fouling problem, was well founded.

The working party therefore recommended that all ships fitted with modern, high-forcing-rate boilers should be converted to burn DIESO in place of FFO. There were obvious operational and logistic attractions in converting the entire fleet but it was felt that the cost and effort involved could not be justified for older ships. This was because of their generally shorter expected lives, the greater technical difficulties involved, and the fact that the effects of fouling were less severe in the lower-rated boilers. These recommendations were accepted in 1966 and a conversion programme was put in hand.

Conversion to Dieso

Conversion of ships posed no great technical difficulty. The major work items required were:

(*a*) chemically cleaning boilers and economizers externally;
(*b*) cleaning fuel tanks and systems;
(*c*) blanking steam supplies to FFO heaters and tank-heating systems;
(*d*) recalibrating tanks to take account of the different specific gravity of DIESO;
(*e*) retuning control systems where fitted,

and these were carried out by H.M. dockyards tasked with carrying out the conversions. Needless to say, the change did not prove to be quite as painless as this and a number of in-service problems rapidly came to light. Two problems, in particular, had been expected:

(*a*) Accelerated fuel-pump wear, arising from the poor lubricity of DIESO—in the event, this was not significant.
(*b*) General fuel leakage, arising from the penetrative properties of DIESO. In this case foresight failed to anticipate that the sealing compound in use in lubricated plug valves was DIESO soluble. As these valves were fitted extensively on boiler-front systems, a particularly hazardous situation had arisen. In the immediate short term an alternative sealant was found but R.N. policy is now to fit ball valves.

Unforeseen Problems

Air/Fuel Ratios

When burning FFO, boiler operators in the Royal Navy had traditionally used the absence of visible smoke in the boiler uptakes as an indication of more-or-less correct air/fuel ratio. Under prolonged steady-steaming conditions the forced-draught fans were trimmed so that the light-brown haze just disappeared from the uptakes. This indication, used in conjunction with occasional inspection of flame shape and condition, had proved to be perfectly adequate and so no provision, beyond uptake viewing periscopes, had been made for measuring air/fuel ratios. It was found that, when burning DIESO, the margin between black and white smoke was very much wider and therefore a clear funnel was no guarantee of an even approximately correct air/fuel ratio.

The effect of steaming with an air/fuel ratio substantially higher than stoicheiometric is to increase the quantity of SO_3 in the combustion products. The efflux temperature is also found to rise but, unfortunately, so does the dew point of the acid which can form. The characteristics of naval boilers are such that marginal conditions exist, particularly at low powers, for acid formation. If measures are not taken to prevent condensation on the external surfaces of boilers as they cool, the acidic deposits will be washed down into the boiler itself causing vicious corrosion around tube roots.

Steaming with low air/fuel ratios causes a reducing atmosphere in the furnace which leads to a characteristic discolouration and crazy cracking of brickwork surfaces. The higher proportions of CO in the combustion gases, resulting from low air/fuel ratio, can also lead to afterburning in the uptakes if there is significant gas-casing leakage above the furnace.

These consequences of steaming with incorrect air/fuel ratios were gradually recognized in ships after conversion to DIESO burning. There was an obvious need for an accurate method of determining the correct air and fuel inputs to naval boilers. Direct air and fuel measurement would have posed technical difficulties in existing installations. However, existing parameters were available to represent these quantities.

Atomizers in R.N. service were regularly and carefully calibrated and could therefore be used as measuring orifices for fuel flow, taking fuel pressure at the burner as the measured variable. It was also found that relationships could be established between air flow through the registers and register draught loss (RDL) sufficiently reliable to use RDL as an indication of air flow. Not all R.N. boilers were instrumented to indicate RDL but it was a relatively simple matter to install manometers.

Programmes were therefore developed, relating RDL to burner fuel pressure for the necessary air/fuel ratio, for each type of boiler to be converted to DIESO burning and RDL manometers added to existing boiler instrumentation where necessary. In addition, greater emphasis was placed on the correct care of boilers when cooling down and standing idle. These measures have resulted in a significant lessening of the problems associated with inadequate control of air/fuel ratio. A modification programme is in progress to provide installed air heating in those boilers not fitted with simmering coils.

Water in Fuel

In marine applications there is a high probability of salt water being present in fuel tanks, even when it is not deliberately introduced for ballasting purposes. Water forms a stable emulsion with FFO which will burn at water concentrations of up to 40 per cent., though not without deleterious effects on boiler brickwork. FFO also acts as an excellent preservative on steel tank surfaces. Thus, relatively small quantities of water present in FFO systems had never posed a real problem, though operators had always been aware of the danger from, and taken precautions against, gross contamination.

The nature of DIESO, however, is quite different. DIESO will not mix with water to any significant degree and any water present rapidly separates out into discrete 'pockets' at the low points of the system. There is, therefore, a very real possibility that any water which passes through the system to the boilers will arrive as a 'slug'. This, when it reaches the atomizers, will almost certainly cause a total 'flame out' of a boiler; potentially a very dangerous situation. DIESO also differs from FFO in that it offers no protection to steel surfaces against corrosion by any water present, particularly salt water. Thus the bottoms of tanks and the low points of pipe systems become very much more vulnerable to corrosion.

To meet, if not to overcome, these problems operating drills for fuel handling have been made more rigorous. Storage tanks are invariably 'stripped' after fuelling and before transferring fuel. Methods of testing tanks for water have been improved. Individual boilers in multi-boiler installations are, wherever possible, supplied from separate fuel service tanks. These measures are largely successful in maintaining integrity of fuel supplies to boilers. Corrosion, however, remains more of a problem than when using FFO. The higher maintenance load in this area is accepted by the Royal Navy in preference to the very expensive application of high-grade coatings to internal tank surfaces. These are only used in tank systems which are deliberately and regularly sea-water ballasted.

Furnace Explosions

Perhaps the most alarming development after the DIESO conversion programme was put in hand was a rash of furnace explosions, six in 1968 alone. One particular class of ship predominated in the list of casualties and it was subsequently established that a shortcoming in the design of the boiler installation in this class was a contributory factor. The underlying cause of all the explosions, however, was failure to recognize and make adequate provision for the increased volatility of DIESO compared with FFO. In the case of nearly every explosion it was shown that either:

(*a*) a flame had been introduced into a furnace which might have been expected (in retrospect) to contain a sufficient quantity of fuel vapour to cause the explosion, or

(*b*) fuel had been admitted to a hot but unlit furnace at a temperature greater than 260°C.

Situation (*a*) commonly occurs on lighting up if fuel has been admitted to the furnace before the flame is introduced, on relighting after involuntary flame out and possibly after partial flame out. Situation (*b*) might occur after total flame out caused by momentary loss of fuel (water slug or transient blockage in supply pipework) followed by immediate restoration of fuel supply.

It has been estimated that as little as one pint of DIESO in a typical frigate furnace is sufficient, under the right conditions, to produce an explosion powerful enough to damage the boiler if a source of ignition is applied. The situation is aggravated by the fact that brickwork fired on DIESO does not develop a glazed surface, as when fired on FFO, so that significant quantities of fuel can be absorbed into brickwork and not be visible.

Stringent rules for the drill to be followed before lighting up, particularly after flame out, have been introduced into R.N. practice. These include a mandatory period of at least five minutes for air purging furnaces before lighting up and after the furnace has been sighted clear of visible fuel, either lying on the floor or issuing from burners. This has necessitated an improvement in furnace viewing arrangements. Strict control of the actual ignition is achieved by ensuring that the flame is introduced, by means of a torch igniter, before fuel is admitted to the burners.

These measures are sufficient, if rigorously applied, to avoid situation (*a*). There are no known instances of explosions on lighting up when the correct drill has been followed. Situation (*b*) can only be avoided by very prompt action on the part of watchkeepers following flame out. This emphasizes the need for very conscientious watchkeeping and meticulous fuel-handling procedures. It is worthy of mention that no furnace explosions have occurred in R.N. ships when main steaming, all the incidents on record having taken place when lighting up or auxiliary steaming, often with only one burner in use.

Benefits

Despite the unforeseen teething troubles experienced, most of which the R.N. has learnt to overcome or avoid, enormous benefits have accrued from DIESO burning in terms of boiler maintenance effort so that the main aim of the change to DIESO has been achieved.

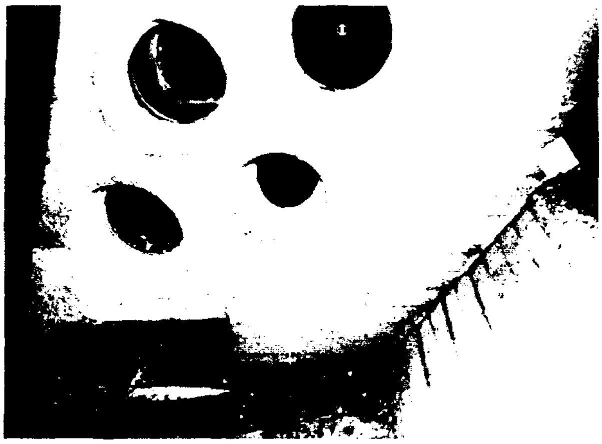

FIG. 4—TYPICAL FRIGATE BOILER FURNACE AFTER 10 000 HOURS BURNING DIESO (FRONT WALL)

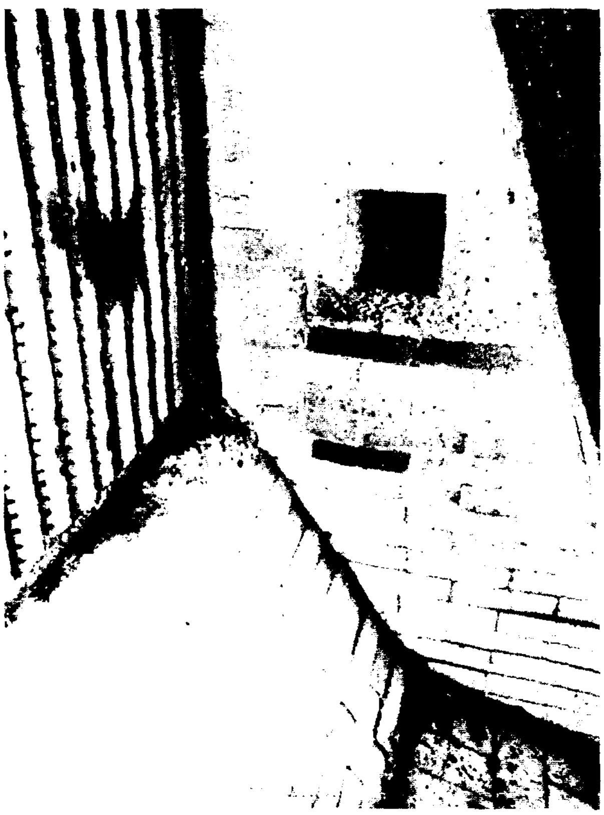

FIG. 5—TYPICAL FRIGATE BOILER FURNACE AFTER 10 000 HOURS BURNING DIESO (BACK WALL)

Tube Nest Fouling

There has been a dramatic decrease in fouling throughout naval boilers. Not only has the quantity of combustion products deposited in tube banks decreased but their nature has changed. DIESO deposits are fine and soft and are easily removed by sootblowing. Regular water washing and awkward mechanical removal of hard slag at 1000-hour intervals has been replaced by dry cleaning, using soft brushes and vacuum cleaners to remove soot from corners not swept by sootblowers, at 1400-hour intervals. Not only is dry cleaning very much quicker, easier and cleaner than water washing but it avoids the attendant hazard to brickwork.

Sootblowing whilst underway has been reduced from a four-hourly to a twenty-four-hourly routine with negligible 'fall-out' on upperworks. This has been estimated to save 90 tons of fuel per year per frigate.

Soot deposition on upper decks, masts and aerials has also significantly decreased with consequent reduction of cleaning and maintenance effort in this area. In fact, R.N. vessels have become generally cleaner, internally and externally, with a marked reduction in the cleaning task. This has led to an improvement in morale of all departments in ships, a not inconsiderable factor to a volunteer navy in a period of social disenchantment with military and itinerant life styles.

Brickwork and Refractory

There has been a marked improvement in the condition and endurance of furnace brickwork and refractory fired with DIESO. This is illustrated in FIGS. 4 and 5 showing views of a furnace after 10 000 hours use with DIESO. These should be compared with FIGS. 2 and 3, views of a similar furnace after 1000 hours of FFO burning.

The maximum life expected from brickwork in an FFO-burning furnace is 5000 hours, with regular repair work required throughout that period. The life of brickwork in a DIESO-burning furnace is largely governed by the quality of the original installation but in the best cases figures of around 20 000 hours are being achieved with only minor patching of refractory during this period.

This improvement has happened because of better quality of combustion, which is largely attributable to the higher and more consistent quality of the fuel and the stricter operating procedures it has imposed.

Superheaters and Economizers

The use of DIESO has overcome the problem of premature failure of superheaters, because of fouling and consequent overheating, and reduced external corrosion of economizers. The lives of these items have been significantly improved and nugatory destruction of perfectly sound boiler parts in order to renew other prematurely failed components has largely been eliminated.

Recent Developments

Since the conversion of all high forcing-rate boilers in R.N. ships, one older ship with lower forcing-rate boilers has been converted to burn DIESO. This was done from considerations other than fouling and with the full knowledge gained from earlier conversions. Operation of this ship has been entirely satisfactory.

The mid life modernization of one class of frigate has included the provision of fully water-compensated fuel-storage systems, necessary to maintain stability margins in the new configuration. This would not have been possible with anything but high-grade distillate fuel because of the emulsifying properties of residual fuels.

The most recent, and possibly the last, major development in R.N. boiler combustion equipment has been the introduction of a steam atomization system, which is a manualized version of that described by Hakluytt and Cooper (3). Early indications are that a further increase in quality of combustion has been achieved with this system which, it is optimistically predicted, will lead to further extensions of sootblowing and external-cleaning intervals and brickwork life. The design of the steam atomization combustion equipment has achieved greater resistance to flame extinction, and that of the associated fuel system higher integrity of fuel supply. These go some way towards off-setting some of the risks associated with this potentially more dangerous fuel. The system has also been fitted to one FFO-burning ship which had a marked soot-deposition problem and it is particularly encouraging that fouling has been virtually eliminated.

Conclusions

The main aim of the change to distillate fuel, to avoid chronic boiler-fouling problems, has been achieved. There has been a very significant reduction in almost every area of boiler maintenance and ship cleaning effort in the Royal Navy following the change. The stricter operating disciplines necessary for dealing with a high-grade distillate fuel have been identified and applied.

It would be impossible to justify the use of DIESO as a boiler fuel by economic considerations alone. However, for the Royal Navy and its particular role, important operating benefits have been gained such as ship availability, flexibility of operation particularly with mixed power plant, world-wide availability of fuel, and improved morale. These are impossible to cost.

Economic factors do have to be considered, however, and rapidly changing trends in world oil prices may yet cause a reassessment of the situation. Advances in the performance of combustion equipment, made since the decision to adopt distillate fuel, offer an alternative solution to the fundamental problem. Nevertheless the essential need to provide increasing quantities of DIESO for diesel and gas-turbine engines, coupled with the increasing difficulty of obtaining FFO of appropriate viscosity for warships, makes continuing use of FFO logistically less and less attractive.

Acknowledgement

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