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TRANSACTIONS (TM)

PURGING OF MARINE BOILERS
Full-scale and Model Investigations

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Purging of Marine Boilers: Full-scale and Model Investigations

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SYNOPSIS

In 1976, an auxiliary boiler furnace explosion occurred on board a VLCC when attempts were being made to relight the boiler during safety valve testing. The investigation of this incident showed that it could not be attributed to faulty operation and was probably due to a gas pocket in the bottom of the boiler uptake not being cleared during purging. Experiments using cold, air flow, scale models of typical main and auxiliary boilers were undertaken using both flow-visualisation techniques and tracer gas concentration measurements. These showed that, apart from certain minor points, the type of main boiler tested purged well and in a reasonable time. However, in the auxiliary boiler uptake a large, stable gas pocket formed and cleared only very slowly. Simple modifications tested on the model reduced the purge time. Full-scale comparative tests on actual boilers were then carried out, using a tracer gas technique, and confirmed in general the results of the model studies although certain discrepancies were found. It was confirmed that the explosion had been due to a purging failure. The investigation has also revealed certain aspects of boiler design which are liable to cause purging problems, and the inadequacy of the present British Standard guidelines on safe purging procedures.

INTRODUCTION

In July 1976, a furnace explosion occurred in the auxiliary boiler of a steam driven 300 000 dwt VLCC during safety valve testing. At the time, the boiler was being re-lit (the fuel in use was unheated gas oil) in order to float the steam drum safety valve after the superheater safety valve had been successfully tested and gagged. The investigation of this incident showed that the cause could not be attributed to any departure from established correct operating procedures. Further, the damage to the boiler indicated an explosion of residual gases in the bottom of the uptake gas space (ie, the space between the last row of tubes in the generating bank and the entrance to the uptake ducting to the superheater). The explosion investigation report concluded that a failure effectively to purge the uptake gas space of fuel was probably responsible for the incident.

Subsequently, model testing of boiler purging was undertaken at the Simon Engineering Laboratories, University of Manchester. This paper is a report on the model studies and also on actual full-scale purge tests which were later thought to be advisable. The model studies concerned both main and auxiliary boilers. The auxiliary boiler design tested was that which had experienced the explosion. On the other hand, the main boiler type chosen for test was one which had given no significant purging problems in service.

The advantages of the small-scale model approach in investigations of this type are clear. Many weeks of model test runs may be made for the equivalent cost of one day's full-scale work. Also, and perhaps more important, many minor changes may be made to a model and tested, whereas it would be quite impractical to do this on full-scale plant.

However, model experiments are subject to a range of generally well-understood errors and some aspects of the real situation may be beyond representation in a small model. Some check on the results in full-scale is therefore desirable. Extensive full-scale tests, using a tracer gas, were therefore carried out, partly to check the validity of the model results. The availability of comparable model and full-scale data considerably enhances the value of the overall investigation.

1.0 MODEL STUDIES

1.1 Form of models and prototypes chosen

Both main and auxiliary boilers were modelled on those fitted on board the ship in question. They were designed by Foster Wheeler Power Products Ltd, and built under licence by the Mitsui Shipbuilding and Engineering Co Ltd, of Japan. The manufacturers' drawings of the boilers were used as a basis for the models.

A scale of 1 to 12.5 was chosen as this resulted in models of convenient size and also allowed some easily obtained materials to be used to represent boiler tubes. The models were designed so that cold, atmospheric pressure air flow could represent the combustion air flow in the purge mode. Water flow models were considered because they would have had less Reynold's Number error but were not used because of the increased cost of manufacture and complexity of operation.

Dr. Dye graduated in Mechanical Engineering at Manchester University and continued as a research student and later as a member of the teaching staff. He has (until recently) been in charge of the Gas Dynamics Laboratory at the Simon Engineering Laboratories and involved in research and consulting work for industry in the general area of industrial aerodynamics, particularly in experimental model investigations and, where necessary, full-scale tests. Problems studied include flow-induced vibration of heat exchangers mainly in nuclear power applications, blade vibration in aircraft gas turbines, industrial ventilation and various wind flow problems with buildings and structures including vibration, pollution and environmental aspects.

1.2 The main boiler model

The main boiler model, which is the simpler of the two types to make, was produced first. The prototype is an ESD III type main boiler, roof fired with four registers. Fig 1 shows a simplified sectional drawing of the boiler and Fig 2 photographs of the model.

The model consists essentially of a box built from clear Perspex sheet to follow the interior shape of the boiler gas spaces. The model is restricted to the region between the burner inlets in the furnace roof through to the uptake, on a level with the steam drum. The remainder of the uptake duct work, economizer and stack were not included as they were outside the regions of primary interest and would not affect the basic flow in these regions.

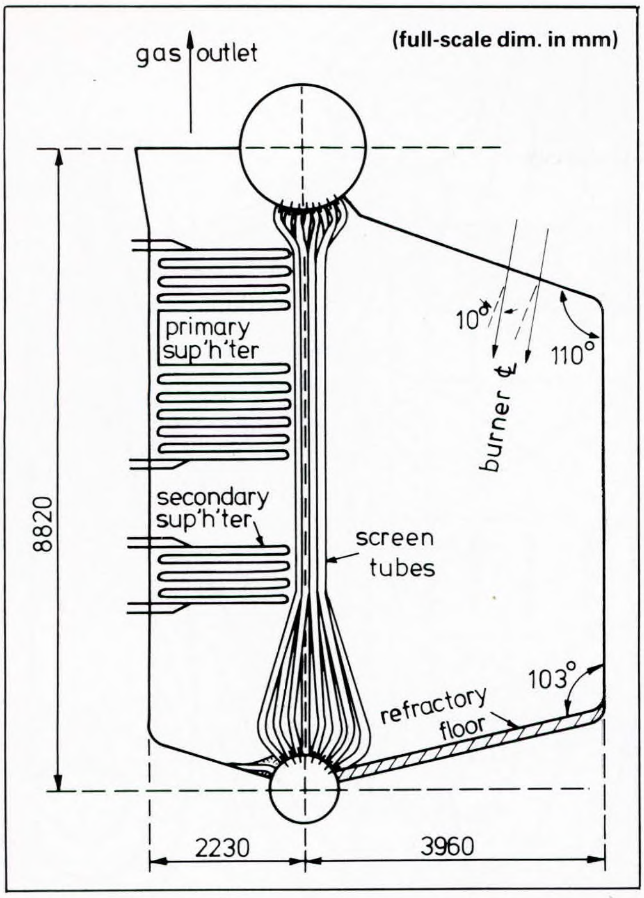


FIG 1 Simplified sectional elevation of main boiler modelled

In the ESD III boiler the screen tubes present a solid barrier to the gas flow from the steam drum down to just below the secondary superheater, and in the model they were represented by wood and Perspex blocks of the correct external shape. Only in the lower region of the superheater screen and its connection to the water drum was it necessary to represent individual tubes. Tubing within 2 per cent of the correct scale size was used and the number of tube rows adjusted to maintain the correct flow blockage.

Gas flow in the uptake over the superheater banks must be generally axial, without swirl or cross-flows, so it was not thought necessary to model individual tubes in these banks. Instead, whole pendants were represented by plates parallel to the flow direction, thus very much simplifying construction of the model.

1.3 Main boiler flow system

Actual details of the wind box and registers were not represented on the model as this would have required unnecessarily complex model work. The registers were represented by turned brass units mounted through the furnace roof at the correct 10° inclination. In these the discharge throat and quarl were accurately represented and preceded by a fairing section to match up to the ducting used in the air supply system.

The flow systems for this model consisted of a small centrifugal fan, connected to ductwork containing the necessary intake, control valve and orifice plate. The fan unit was connected to the model by flexible tube and a simple manifold used to distribute the flow amongst the four registers. Tests showed this distribution was even within 5 per cent. The registers could be removed and replaced by plugs so that the model could be run using any combination of the four registers. For most of the test programme, swirlers were not fitted.

1.4 Model test procedure

1.4.1 Flow visualisation

The model was made largely of Perspex to allow visualisation of the gas space flow patterns. To investigate purging, the model was initially filled with smoke and then purged with clear air. Fig 3 shows the idealised flow pattern for the central regions when purging with all registers. Ciné film of these results has been obtained.

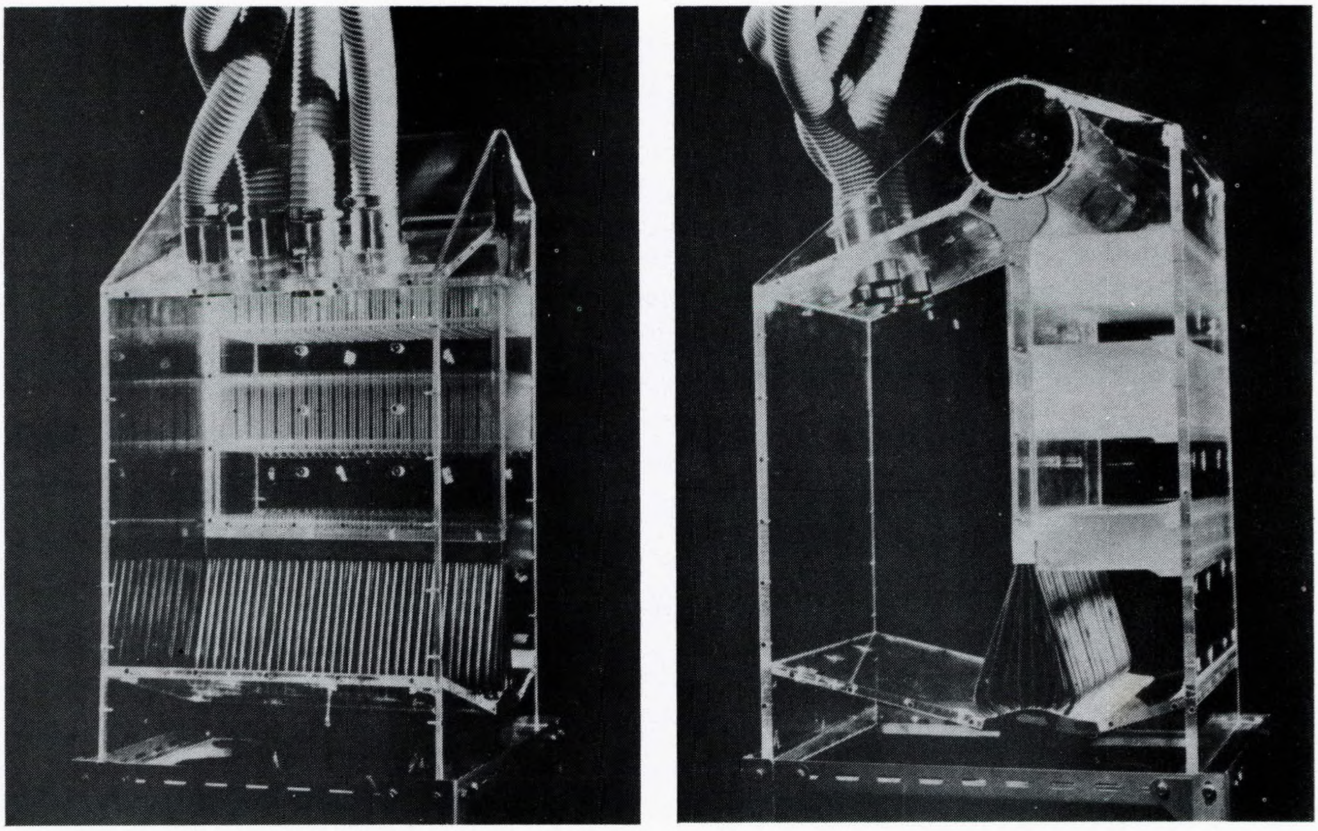


FIG 2 Main boiler model: the prototype is an ESD III, roof fired with four registers

As expected, the visualisation results show that the ESD III type of boiler purges well. However, two points of interest emerge. Firstly, the basic re-circulation pattern from the furnace floor region back up to the ignitor location shows that vapour boiled off any fuel spillage on the refractory floor of the furnace would be fed directly to the source of ignition on re-lighting. Secondly, the upper region of the furnace, near the steam drum, is the last area to be purged. There was no evidence of any gas pockets in the regions of the uptake as modelled.

1.4.2 Gas concentration tests

The second (and major) series of tests carried out with the main boiler model comprised measurements of the concentration of carbon dioxide, with which the model was pre-filled, at various points in the boiler gas spaces during a simulated purge. The CO_2 was used to represent unburnt fuel, products of combustion, etc, supposed to be in the boiler at the start of the purge.

To detect CO_2 concentration, a commercial instrument sold for leak detection was employed. This operated on a comparison of the thermal conductivity of the test sample with a "clear air" source. On calibration this instrument was found to give an output linearly related to the concentration of CO_2 provided that certain secondary effects were eliminated. The detector withdrew its sample from the model at a rate of about 3ml/min and thus had only a very small effect on the model flow balance. A transport time delay of about 1s was involved in drawing the sample through the standard probe to the detector head.

Measurements were made at each of 32 locations (in 6 groups) of the model as shown in Fig 4. Some of these readings were taken at the surface and others at the scale equivalent of 0.3m or 0.6m into the boiler. In all cases the model was pre-filled under zero flow conditions with CO_2 up to about 60 per cent concentration. The model fan and the output chart recorder were then started simultaneously and CO_2 concentration against time graph drawn automatically, (see Fig 5). In most cases the model was operated in real time, that is, the fan caused the same number of volume changes of the furnace per unit time as in the real case.

Table I gives the results obtained, all for a flow equivalent to 100 per cent combustion air, using all four registers. The interpretation of the results in terms of absolute explosive limits proved difficult. Had the maximum likely concentration of fuel vapour in the boiler before purging been known, it would have been simple to simulate this and then to determine the time required to purge down to the safe explosive limit. However, as no specific information on the likely initial condition was available, the results were analysed in terms of the time required to reduce the initial arbitrary concentration in a series of stages down to 1 per cent of the starting value. This time is likely to be an over-estimate of the purge period required in practice.

For many of the test points in the furnace roof and uptake regions,

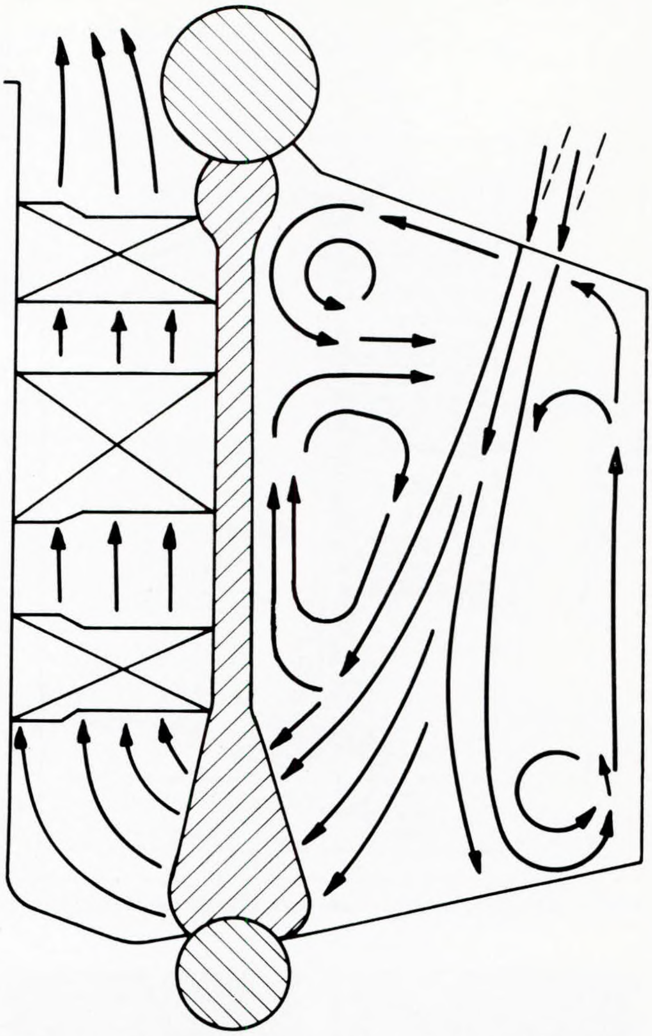


FIG 3 Idealised basic flow pattern for centre of main boiler model (all registers in use)

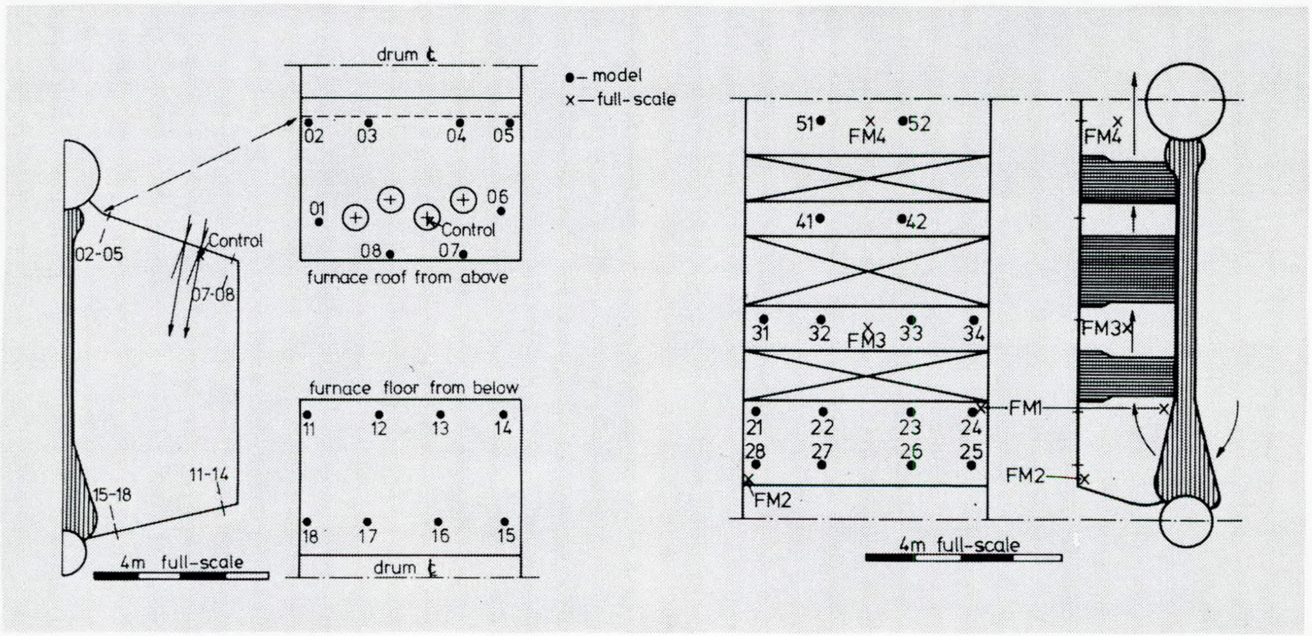


FIG 4 Sample points for main boiler and model test locations

the concentration rose initially and then fell away. This result was to be expected due to the non-homogeneous initial distribution of CO_2.

Assessment of the data given in Table I shows marked differences in purge times for closely neighbouring test locations and even between multiple tests at the same location. These discrepancies are present in the shape of the purge curves as well as in the ultimate times needed to reach a given concentration. Although part of this variation must be due to experimental error, it should be remembered that the unsteady and swirling nature of the furnace flow will lead to a certain amount of randomness in the real purge performance. It is doubtful whether sufficient results have been taken, for absolute faith to be placed in average values. However, these results do give certain fairly clear indications of purge requirements.

In general, the furnace roof area required longer to purge than either the furnace floor or the superheater space (Region 2). Further, the roof area by the steam drum is slower to purge than the region below the registers and these findings would have been expected on the basis of the flow visualisation experiments.

The uptake regions (3, 4, and 5) generally purged clear after the furnace floor but before the roof area. At first sight this appears strange as all the contaminant must leave the boiler via the uptake. However, the roof corner region is small compared with the furnace as a whole and the registers are supplying relatively large air flows, so that the mixture, formed by the slow clearance of this region and passing through the uptake, must have a very low concentration of CO_2.

It appears, therefore, from both flow visualisation and gas concentration test results, that the critical area for purging is the pocket formed by the intersection of the screen tubes, steam drum and furnace roof. However, the results do not give any serious cause for

Table I Analysis of purge times for model main boiler*

Location			Time (s) to reduce to given % of initial concentration					
Surf.	0.3m	0.6m	50	20	10	5	2	1
01			7	11	14	21	27	45
02			7.5	14	19.5	24.5	29	35
03			5.5	12.5	15.5	25	33	50
03			7.5	14.5	21.5	27	32	40
04			6.5	11.5	15.5	19.5	27	35
04			8	12	16.5	21	31	45
		04	8	13	17	22	28	40
05			8.5	14	18.5	23.5	35	50
06			7.5	13.5	16	20	27	40
	06		6.5	11	15	19	23	40
	06		6.5	11.5	13	19	22	50
	06		6.5	11	17.5	24	30	40
	06		6	11	15	20	25	40
		06	6.5	12.5	16	19	28	40
07			7.5	11.5	16	20.5	25	35
		07	7	11	14.5	19.5	27	40
08			7.5	12	16	22	29	40
		08	7	11.5	16	21	27	35
		08	7	12	16	22	26	45
11			4	8	15	23.5	34	40
12			4.5	8.5	12.5	20	34	40
13			7	9.5	13	16.5	21	28
14			7	10	13.5	17	24	32
15			5.5	9.5	12	18	25	28
16			2	4.5	10.5	15	21	27
16			4	8	16.5	23	29	33
	16		3.5	8.5	15	23	31	35
17			4	8.5	13	16.5	22.5	30
18			7.5	10.5	15	19	25	27
21			7	12	16.5	20.5	23	25
		22	6.5	12.5	15.5	19	22	32
		23	7	12	16.5	20.5	25	28
		24	5	9	12.5	18	24	30
25			7.5	11	13.5	19	24	27
26			8.5	13	16	21	24	30
		27	7.5	11	13.5	18.5	24	35
		28	7	10	15	22	28	32
		31	7	12.5	18.5	23.5	27.5	30
		32	5.5	11.5	15	18.5	27	35
		33	7	13	19	25	31	40
		34	6	10.5	15	19	25	30
		41	7.5	12.5	17.5	21.5	25	30
		42	8	13.5	16.5	21	24	35
		51	8.5	12.5	17	22.5	32	55
		52	8	13.5	18.5	23	28	34

*(100% flow, all registers— but note that this flow is 90.21% of the "full" flow for the equivalent full-scale test). Test locations are shown on fig 4.

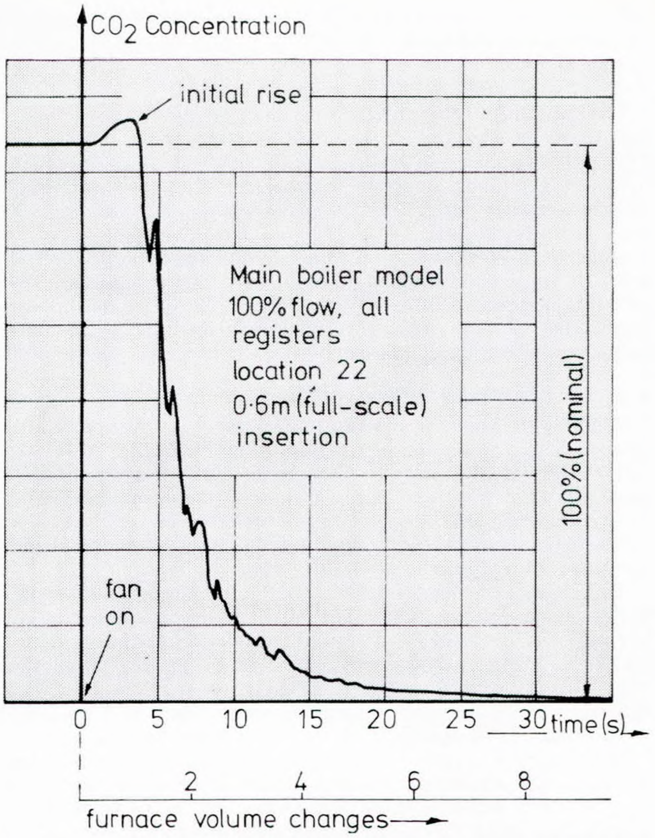


FIG 5 Tracing of typical CO2 concentration fall during a simulated purge

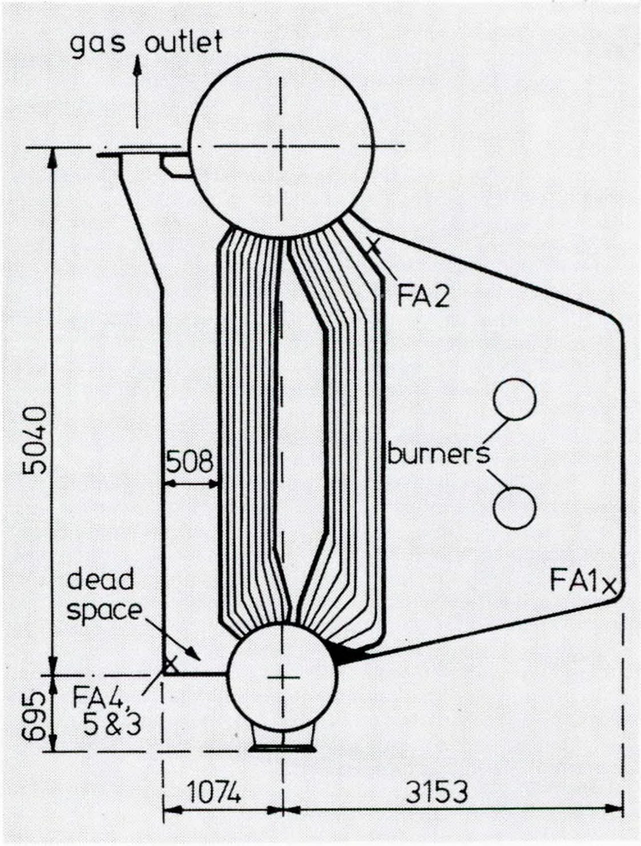


FIG 6 Simplified sectional elevation of auxiliary boiler modelled (full-scale dim. in mm) showing full-scale sample points

concern since a typical purge time is one minute at 100 per cent air flow, for this type of boiler.

1.5 The auxiliary boiler model

The boiler modelled is an ESD Auxiliary type with two registers and side wall firing. Fig 6 shows a simplified section of the actual boiler and Fig 7 a photograph of the model. In scale, general form and materials of construction, the model is identical to that of the main boiler described earlier. However, it was necessary to represent all the individual screen tubes.

Again the number of tube rows was adjusted to maintain the correct blockage whilst compensating for slight inaccuracy in scale size. The model flow system was also similar to that used for the main boiler except that, in view of the lower flow rates required, a gap-meter (rotameter) was used to indicate flow rates.

1.6 Auxiliary boiler model tests

Basically the same test procedure as for the main boiler model was employed, except that the visualisation results obtained were so clear that it was only necessary to make confirmatory tests by the CO_2 concentration technique at one point in the last region to be purged. In the visualisation tests the furnace and upper regions of the uptake cleared quite rapidly but a large and very stable smoke pocket remained in the bottom of the uptake as shown in Fig 6.

This region is shielded by the water drum from the main flow in the boiler and cleared only very slowly over a period of many minutes of purging. The last residual pocket was at the burner end of this space. As in the previous case, a ciné film record of the purging process was made but, as the process was so clear and stable, an alternative record was taken in the form of a sequence of still photographs. Fig 8 shows extracts from this sequence for 15s and 1min after start of purge.

By taking measurements from the full sequence of photographs, the volume of the residual gas pocket was estimated, and Fig 9 shows the form of the decrease in this volume with time. Small quantities of smoke remained in the model for up to 8 min at the full purge rate.

1.7 Visualisation tests on modified auxiliary model

A series of possible modifications to the internal shape of the boiler gas space in the critical region, as shown in Fig 10, were tested by the visualisation technique. Table II shows the resulting purge times. It can be seen that various ways of filling the dead space, with or without deflector vanes, produced an acceptable purge time. Figs 8 and 9 show a clear comparison between the "as built" condition and the modification proposed by the manufacturer, following discussions of early test results.

The perhaps more obvious solution of a secondary fan to purge the dead space was not tested as it was understood that the complications of such a system would be undesirable and a "passive" modification much to be preferred.

1.8 Accuracy of the model simulation

Model tests of the type described are known to be subject to several errors. There must be approximations and in models of the type used much fine detail in the actual plant cannot be reproduced in the model. In a geometrically similar model, such as those used, scale effects mean that the ratios of velocities at different points may not be correct. Generally, model tests are run at an incorrect Reynold's Number although experiments with the existing models at various flow rates have not shown any conclusive evidence of this effect.

Both models were made without swirlers, thus introducing a further possible error. To investigate this, partly representative swirlers were made. Visualisation tests on the main boiler model showed that the swirlers slightly increased the spread of the inlet jet, but no difference could be detected in the general purge performance. The addition of both right and left-hand swirlers to the auxiliary boiler model had no noticeable effect on the purge behaviour either.

In neither model was it possible to simulate bouyancy effects resulting from heating of the gases by the furnace walls. Such effects may be significant in the auxiliary boiler as, when the model was inadvertently exposed to considerable heating from photographic lights, the resulting natural convection tended to destroy the otherwise stable nature of the residual gas pocket.

As the model work had predicted that an unacceptably long purge period was likely to be required for the auxiliary boiler, the full-scale test work described in the next section was undertaken. The aims of this study were, firstly to confirm the model findings and, secondly, to determine the minimum purging times required for these boilers.

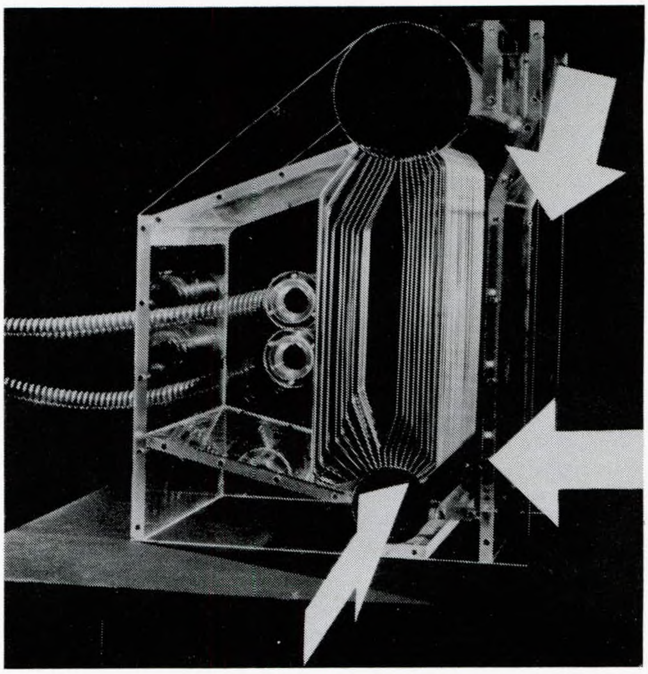


FIG 7 Auxiliary boiler model (arrows show directions from which views in Fig 8 were taken)

Table II Purge times from model visualisation for the auxiliary boiler with the modifications shown in Fig 10.

Arrangement No.	Class of modification	Purge time (min) at 100% flow, using both registers
as built	—	6 to 8
1	raised floor	2½
2		2½
3	inclined ramps	2½
4		2
5		1½
6		1½
7		1¼
8		1
9	deflection vanes	2½ to 3
10		3
11		1½
12		1
13*		1
14*		1 to 1¼
15	prismatic deflectors	1½ to 2
16		1
17		1 to 1¼
"modified"	raised floor with inclined section	1¾

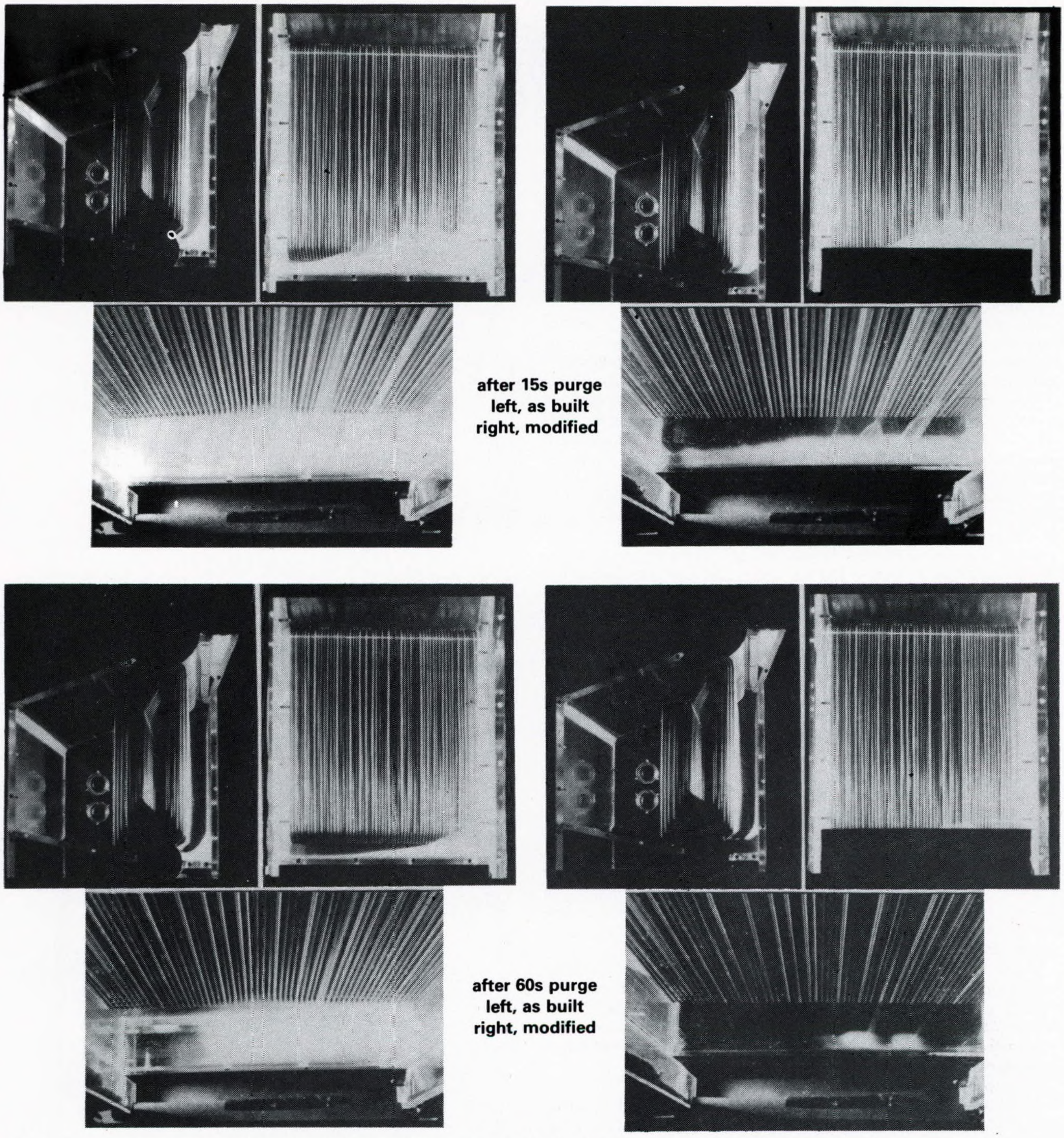
*small secondary vanes fitted normal to the vane shown on Fig 10.

2.0 FULL-SCALE TESTS

2.1 Boiler types tested

Full-scale tests were carried out on main and auxiliary boilers of two types for the reasons given in the previous section. Firstly, the Foster Wheeler Power Products types were tested on the ship which suffered the original auxiliary boiler explosion (these were also the actual boilers modelled). At a later date similar tests were made on the Babcock and Wilcox main and auxiliary boilers of another ship of about the same size.

The tests were arranged and conducted by personnel from Shell Research Ltd (Thornton Research Centre) and Shell International Marine Ltd. The author was present at the tests on the Foster Wheeler boilers.



after 15s purge
left, as built
right, modified

after 60s purge
left, as built
right, modified

FIG 8 Smoke visualisation of auxiliary boiler model: model pre-filled with smoke then purged at 100% flow (both registers)

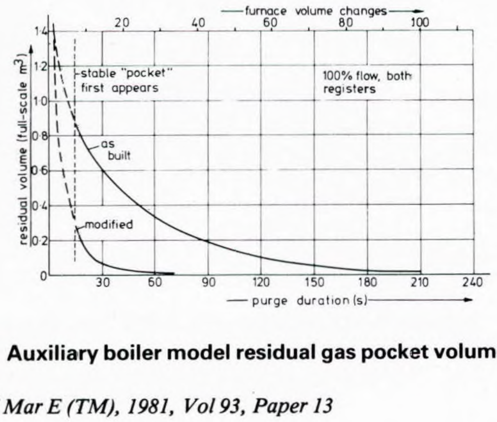


FIG 9 Auxiliary boiler model residual gas pocket volume

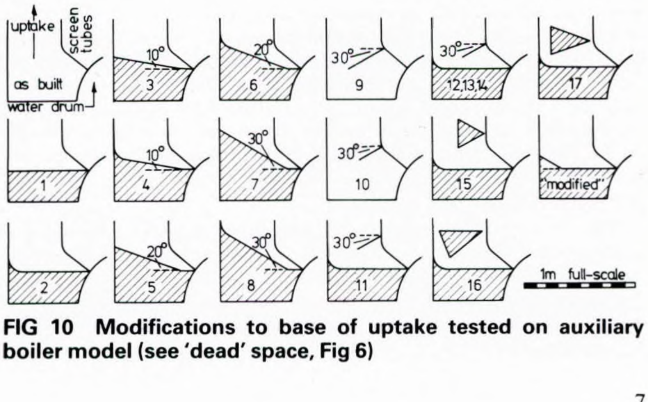


FIG 10 Modifications to base of uptake tested on auxiliary boiler model (see 'dead' space, Fig 6)

2.2 Full-scale test technique

The tests were, in both cases, conducted at the end of a re-fit period with the boilers cold, but with power available to operate the forced draught fans. The fans were run at various flow rates that were measured using the standard instrumentation fitted to the ship.

Again a tracer gas technique was used. In view of the very large volumes involved, a tracer which could be detected at very low concentrations was necessary. Sulphur hexafluoride (SF_6), supplied at 10 per cent concentration in nitrogen, was used as it was readily available and could be recorded at concentrations down to 1 part in 10^8 by the detector used and was heavier than air. This commercially available leak detector operators by electron capture and employs a nickel-63 source. The detector includes a small suction pump which draws a continuous sample through the instrument. Its output is an electrical voltage proportional to SF_6 concentration; this was recorded on a multi-pen chart recorder.

Six such detectors were employed, each connected to the appropriate test location by equal lengths of nylon tubing so that the transport time delays would be equal for all. The sample tubes were secured in the chosen places by a system of wires and magnets.

It did not prove possible to carry out the full-scale tests in the same manner as the model tests for various technical reasons. In all the cases reported here, tracer gas was injected at a steady rate into the forced-draught fan intake whilst the fan was run at the required test condition, giving a concentration of 20 parts per million at the registers. Injection was continued until all the detectors showed full-scale deflection on their most sensitive range (which corresponds to a SF_6 concentration of approximately 4 ppm).

The tracer gas supply was then turned off and the decay of the SF_6 concentration at the various test locations, relative to one detector in a register, was monitored until all the detectors showed a concentration of less than 5 per cent of the original value, when the boiler was considered to be purged.

2.3 Test locations and results

2.3.1 ESD III main boiler

Model tests had shown that the existing 50s purge period was probably adequate to clear the boiler furnace, with the exception of one area near the steam drum. Unfortunately it proved impossible to reach this area with the equipment available. Also, a minor explosion had occurred in the superheater/economiser section of this boiler, so it was decided to concentrate the full-scale test locations in this region.

The points chosen are shown on Fig 4. Note that, in this and all the other tests, one sample point was placed in a burner register to give a time reference for estimating the purge period. A typical output trace is shown in Fig 11 with the pen 'stagger' removed, and the results are presented in Table III. Note that on Fig 11, 'control' is the detector in the register; the direction of change in the graphs depends on the wiring polarity (all concentrations *fall* at positive times), FM 2 shows also the falling phase at -15s.

It can be seen that the majority of the superheater/economiser section purges within 40s, except for the sample point in the bottom outside corner below the superheaters. There is no evidence in these results which would explain the minor explosion that occurred near test location FM 4. Also the reduced flow rate causes a corresponding increase in purging time required.

2.3.2 Foster Wheeler auxiliary boiler

As the model test had shown that the bottom of the uptake space would be the last to purge, three sample points were arranged along the length of this area, all in the outside corner. To provide comparative data for possible further model tests, two other sample points were arranged in corners of the furnace. These locations are shown on Fig 6 and the test results given in Table IV.

The full-scale results confirm the model predictions that the base area of the uptake purges only slowly, requiring at least 3min at full purge flow to clear. A detailed comparison of the results is given in Section 3 of this paper. Again, reduced flow rates result in increased purge times, although, in this case, the results do indicate that the boiler purges more efficiently (in terms of volume changes) at the lower flow rates.

2.3.3 Babcock and Wilcox main boiler

The tests on the Babcock and Wilcox boiler types were intended to complement the previous tests and not for specific comparison with model results. Consequently, the test locations were distributed in both the furnace and the superheater/economiser section as shown on Fig 12. Table V gives the results obtained (using the same test procedure as before).

The purge times in the table are significantly longer than for the ESD III boiler previously tested as the burner control system sets the purge flow at 40 per cent of the maximum combustion air flow, rather than the 100 per cent of the ESD III. If these results are adjusted for flow rate equivalence, there appears to be no significant difference in the purge times.

The control system logic sets a minimum purge period of three minutes for any purge flow rate above the minimum acceptable level of 25 per cent. At any flow rate below 40 per cent, location BM5 would

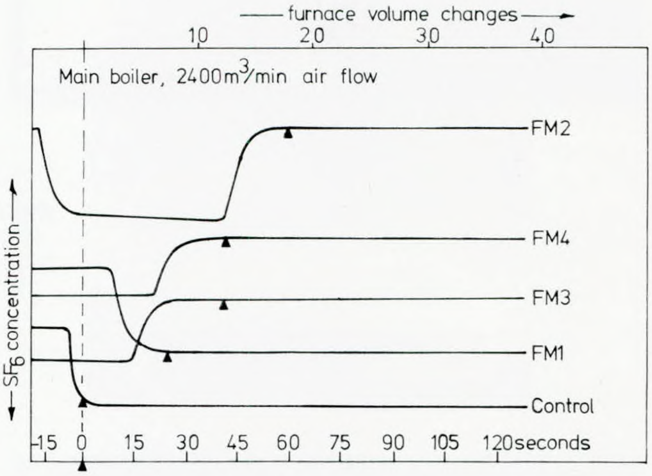


FIG 11 Tracing of a typical full-scale test result

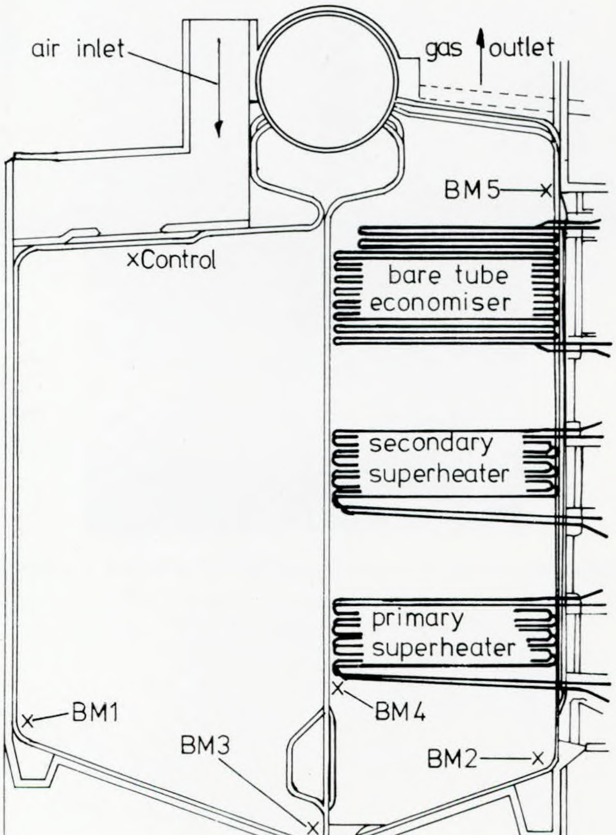


FIG 12 Babcock & Wilcox type main boiler, showing full-scale test points

not purge satisfactorily within this time, although in practice a 40 per cent purge flow is always used.

2.3.4 Babcock and Wilcox auxiliary boiler

From Fig 13, it is clear that this boiler differs significantly from the Foster Wheeler type in that it is roof fired. The shape of the uptake base by the water drum is also very different. The test locations chosen for this boiler were in groups on the furnace and uptake floor areas, as shown in Fig 13. Table VI gives the test results which reflect the design differences and do not show any slow purging region. At maximum purge flow, the maximum time recorded, 1min 50s, is well within the three minutes set time for this boiler.

3.0 COMPARISON OF MODEL AND FULL-SCALE

3.1 Foster Wheeler main boiler

Opportunities for direct comparison between model and full-scale data are restricted by differences in test locations used. Model data exist mainly for the furnace region but it was not practical in the full-scale tests to install detectors in the upper regions of the furnace. The full-scale test locations were mainly in the uptake, including one (FM4 in Fig 4) in a region not fully represented on the model. This attention to the higher parts of the uptake was prompted by a very minor explosion which occurred there shortly before the full-scale tests were made.

One further complication is that the model experiments were conducted at a "full" flow rate, equivalent to 90.21 per cent of the maximum flow of the actual forced draught fan, so that due allowance for this must be made when comparing the data in Tables I and III.

The full-scale data obtained for two different air flow rates agree approximately with each other on a pro-rata basis and in any case the model tests show that some randomness of the results is to be expected. Comparison of the full-scale and the model purge times for full-scale location FMI shows general agreement although the test locations do not correspond exactly. The model appears to have underestimated the purge time at location FM3 (between the superheaters) by a small amount. Model measurements at what corresponds to full-scale location FM2 were not made, but longer purge times might well be expected in this outer corner of the uptake.

Table III Full-scale purge times Foster Wheeler type main boiler

Sample point (see Fig 4)	Flow Conditions	
	2400m^3/min air flow* (fan speed 1800 rev/min vanes full open)	1600m^3/min air flow (fan speed 1300 rev/min vanes full open)
FM 1	24s	36s
FM 2	58s	1 min 15s
FM 3	40s	53s
FM 4	41s	1 min 10s

*Corresponds to 100% available flow.

Table IV Full-scale purge Foster Wheeler type auxiliary boiler

Sample point (see Fig 6)	Flow conditions		
	1 register 100% air flow	2 registers 63% air flow	2 registers 100% air flow
FA 1	2 min 28s	2 min 12s	1 min 20s
FA 2	1 min 59s	2 min 13s	1 min 23s
FA 3	2 min 41s	2 min 53s	2 min 18s
FA 4	4 min 13s	5 min 14s	3 min 2s
FA 5	2 min 33s	2 min 37s	1 min 28s

Table V Full-scale purge Babcock & Wilcox type main boiler

Sample point (see Fig 12)	Flow conditions (all registers in use)		
	25% Flow (minimum setting)	40% Flow (normal condition)	74% Flow
BM 1	42s	39s	37s
BM 2	1 min 55s	1 min 57s	1 min 50s
BM 3	2 min	2 min 2s	1 min 53s
BM 4	50s to 1 min 50s	45s to 1 min 28s	57s to 1 min 28s
BM 5	4 min 5s	2 min 43s	2 min

Table VI Full-scale purge Babcock & Wilcox type auxiliary boiler

Sample point (see Fig 13)	Flow conditions		
	1 register 100% air flow	2 registers 77% air flow	2 registers 100% air flow
BA 1	1 min 14s	1 min 57s	40s
BA 2	1 min 33s	2 min 40s	1 min 3s
BA 3	2 min 17s	4 min	1 min 50s
BA 4	1 min 31s	2 min 20s	47s
BA 5	2 min 37s	4 min 32s	1 min 35s
BA 6	1 min 13s	1 min 4s	52s
BA 7	1 min 7s	56s	45s
BA 8	1 min 31s	1 min 22s	1 min 12s
BA 9	48s	38s	26s
BA 10	1 min 54s	1 min 25s	1 min 10s

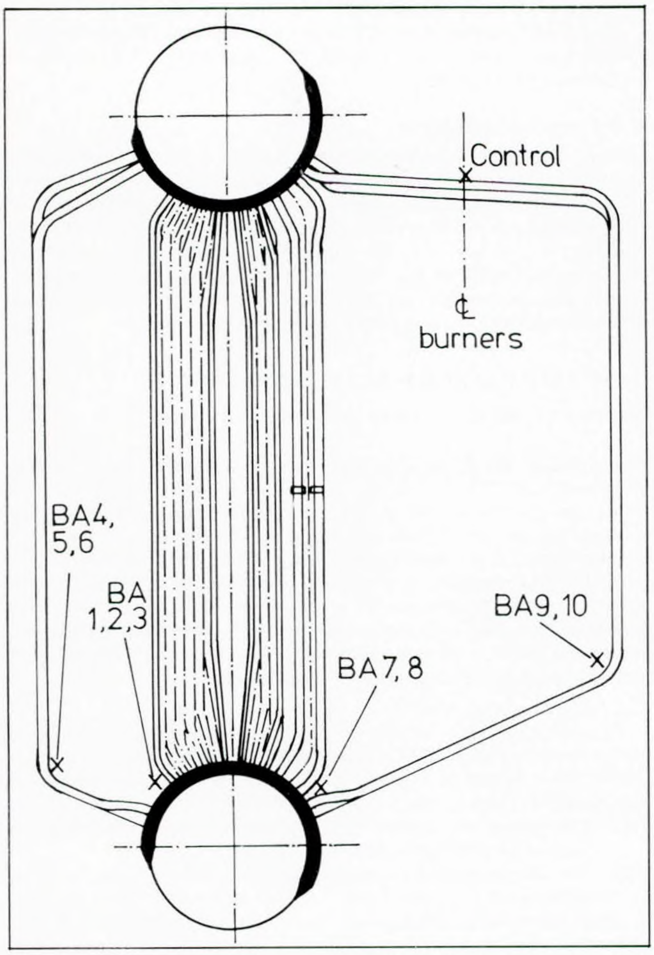


FIG 13 Babcock & Wilcox type auxiliary boiler, showing full-scale test points

3.2 Foster Wheeler auxiliary boiler

In this case, both model and full-scale tests concentrated on the bottom region of the uptake which the explosion damage and the model tests indicated as the critical area. At first sight, the agreement between model and full-scale appears poor, particularly with regard to the "ultimate" time to clear the uptake completely. This was measured as 3 min full-scale and over 6min on the model for the full available purge flow. However, when the results are studied in detail it is found that, with two specific exceptions, the results agree very closely.

A more detailed examination of how the pocket at the bottom of the uptake clears is necessary to explain why the two tests gave apparently different results. The first stage of the purge process, as indicated by the model, is a general clearance of the furnace and the higher parts of the uptake, leaving a well-defined and stable gas pocket in the base of the uptake. This pocket clears slowly and intermittently as small volumes of the gas escape up the outside wall of the uptake. This process reduces the pocket volume until an area of the uptake floor clears: this is approximately three quarters of the boiler width from the burner side and midway between two of the full-scale sample points.

The clear area then spreads in both directions but leaves a still substantial gas pocket at the burner side of the space, whilst clearing two of the full-scale test points. As the clearance continues, the residual gas pocket contracts from both ends until it is clear of the last full-scale measurement point and is centered at about a quarter of the boiler width from the burner wall. At this stage the full-scale tests would indicate "boiler clear".

The difference between the model and full-scale clearance times is the time required to purge away this last residual gas pocket. It should be realised that the actual volumes of fuel vapour which would remain in the boiler at this stage are minute and even if ignited, are unlikely to cause damage. Fig 9 shows that by three minutes the residual pocket volume has fallen to below $0.025m^3$ full-scale.

Examination of the model results shows that the full-scale test location FA4, which was the last to show "clear" in the full-scale tests after a three minute purge, cleared in the model at times varying from 3 to 4½min. The shorter times were recorded when the model was heated by the photographic lights. In view of the differences in the two test procedures and between the model and full scale, such agreement may be considered good.

The first important disagreement between model and full scale concerns the furnace clearance time. The full-scale test locations FA1 and FA2 gave clearance times of 1min 20s and 1min 23s respectively. No actual model measurements have been made at these points, but the furnace was observed to be generally clear in a much shorter time. Further model measurements are necessary to clarify this point.

The second area of disagreement concerns the order in which the three full-scale test locations on the floor of the uptake cleared. In the full-scale tests, the centre location cleared first followed by that by the wall opposite to the burners. Clearance in the reverse order was observed on the model. The only explanation of this discrepancy is that on the actual boiler the centre tapping in the uptake base was located close to an angle steel stiffening frame around a recessed access door which was not shown on the boiler drawings, nor represented on the model, and which might have influenced the local flow pattern.

4.0 DISCUSSION AND CONCLUSIONS

4.1 Model investigations

The model study reported here demonstrates both the advantages and limitations of the technique. Such tests are relatively cheap and simple to carry out and give guidance for any necessary full-scale work. The model study is probably the only practical way to investigate a range of design changes to an object such as a boiler. Apart from limitations in scale detail, several aspects of the exact situation in a boiler cannot be readily modelled and may influence the accuracy of such work. However, it is only through experience gained in investigations such as this that the reliability of model techniques may be demonstrated and improved.

4.2 Full-scale tests

Both series of full-scale tests have provided sufficient data for a short term solution to the problems of inadequate furnace purging. In some cases, however, the increases suggested may result in undesirably long purging times and long term solutions may well involve boiler modifications to change the purging characteristics.

The full-scale test work undertaken has provided valuable data by which to check the accuracy of the model studies. The success of these measurements demonstrates that such tests could be made as a matter of routine when new boiler designs are commissioned. The publication of more such purging data would be valuable.

4.3 The original auxiliary boiler explosion

The results of this investigation support the conclusions drawn from an examination of the damaged auxiliary boiler. These were that the explosion resulted from the ignition of a gas pocket in the base of the uptake which had not been effectively purged. The test results show that a significant amount of fuel vapour is likely to have been present in the damaged region of the boiler, depending in size on the purge period before the explosion. However, the exact mechanism by which this gas pocket was ignited remains unclear. Tests on the model do show that in three to four seconds after admitting fuel to the furnace, a complete trail of combustible mixture will exist from the ignitor to the gas pocket. Whether ignition occurred through this or some other route, its probability must have been low as no other incident has been reported from a number of similar boilers in service.

The results further show that relatively simple modifications to the uptake base, together with a realistic purging period, will remove the risk of another explosion.

4.4 Purging standards

This investigation shows that the various boiler designs tested, including the Foster Wheeler type of auxiliary boiler, when modified to reduce the dead space volume, require to be purged for 20 to 30 volume changes at 100 per cent flow to achieve acceptable clearance. Further, it appears that, for some boilers, there may not be any advantage (in terms of the volume of pure air required) in purging at lower rates. In view of these findings, the requirements of the relevant British Standard (see appendix), should be reconsidered.

5.0 APPENDIX: PURGING, IGNITION AND FLAME FAILURE REQUIREMENTS

Extract from: BS 799: Part 4: 1972 Specification for Oil Burning Equipment (atomising burners over 36 litre/hr)

5.1 Furnace pre-firing purge

The purpose of the furnace pre-firing purge is to dilute to a safe level the explosive mixture that may be present in the furnace and the gas passages of the plant, and for this reason a source of ignition during a pre-firing purge period is only allowed as explained in 5.1.1.

There shall be a minimum delay between purging and admitting any fuel into the furnace. The purge shall be sufficient to change the atmosphere of the furnace volume at least five times. The rate of purging should be at least 25% of the full-load combustion air mass flow to the furnace. Consideration should be given to increasing the rate of purging to at least 50% of the full-load air flow when the furnace is very large, for example, in water-tube boilers for power generation.

Normally, the pre-firing purge time should not be less than 15s except in cases where it has been proved under test that the required five volume changes have been achieved in a shorter pre-purge time.
NOTE: This shorter time period applies to special cases such as flash steam boilers.

Purging in excess of the minimum air changes specified for the furnace may be required, for example, where the relative volume of convective heat transfer sections, flues and chimneys is large, or where there are spaces within which explosive gases or vapours may be trapped.

Furnace volume is the space in which combustion takes place, that is to say, where the furnace walls are subjected to direct radiation from the flame.

As an alternative or as an addition to furnace purging, the atmosphere of the furnace may be tested to check the presence of combustibles. If no combustibles are present, then the pre-purged period can be omitted, or the length of time of the pre-purge period adjusted until the absence of combustibles has been proved. It is essential that a representative sample of the furnace atmosphere is tested and also that the test equipment is designed so that failure of any part of the equipment results in a safe condition.

5.1.1 Electric spark ignition

Electric spark type ignitors may be energized during the pre-firing purge time only when all the following conditions are met:
NOTE: It is preferred that the spark is delayed until the atmosphere surrounding the electrode has been cleared.

(1) The burner and appliance is ventilated by means other than the burner fan during the shut-down period;
(2) The burner control system is designed so that if a flame is present either during the pre-firing purge period or at 5s after the shut-down signal has been given, then the burner shall be locked-out;
(3) The maximum starting capacity of the burner does not exceed 110 l/h;
(4) Gas is not to be used as an ignitor or alternative fuel.

5.2 Failure to ignite

When there is failure to ignite a burner during a starting sequence, a signal to cut off the oil feed shall be given within 5s of oil first entering the furnace. From the moment of the signal to cut off the oil feed, not more than 0.1% of the maximum hourly oil flow shall pass into the furnace.

When the firing rate, throughout the starting cycle is less than 36 l/h, the oil feed shall be cut off within 15s (see BS 799: Part 3).

ACKNOWLEDGEMENT

The author wishes to thank many on the staff in the Shell Group of Companies for their assistance during the completion of the work reported in this paper; in particular Mr. F. D. Gainey of Shell Research Ltd (Thornton Research Centre) whose full-scale test results are included.

Discussion

MR D.S. TURNER (Foster Wheeler Power Products Ltd, R & D Dept): FWPP agrees that the principle of using models is an important boiler 'gas side' design practice; the company has consistently used flow models over the past 20 or so years, having made around 100 models of different types in this time using various analysis techniques. Figure D1 shows a typical marine boiler model.

FWPP prefers generally (though not always) to use water flow models for analysing distribution and optimizing flows as, with suitable tracers, it is easier to view flow patterns. Also, FWPP prefers to model on a basis of reasonable Reynolds' number simulation than proportional volumetric flows, because densities on model and full scale are radically different. With water flows, a reasonably small model can be used; with air flows, the model often becomes large if realistic Reynolds' number and proportional pressure drop modelling is required.

In a totally-enclosed flow model of this type, the flow patterns are mainly governed by a ratio of forces which are defined by the Reynolds' number of the flow. In particular, when purging characteristics are being investigated, it is felt by FWPP that mixing and turbulence are the most important criteria of the flow. Unfortunately, an exact equivalence of Reynolds' number is extremely difficult to achieve in a practical model of this type using air flows, and would also be incompatible with real time modelling.

The author's use of equivalent volume changes per unit time means that the flow velocities are reduced in the same proportion as the dimensions of the model, thus ensuring that the time periods are the same in the model as in the full-scale boiler. As can be seen from the following calculation, the effect shows that the tests were undertaken at a significantly reduced Reynolds' number.

$$V_{(m)} = \frac{L_{(m)}}{T_{(m)}} \quad \text{and} \quad V_{(p)} = \frac{L_{(p)}}{T_{(p)}}$$

For real time modelling $T_{(m)} = T_{(p)}$ and $L_{(m)} = L_{(p)} \times 1/(\mathrm{SF})$

thus $V_{(m)} = \dfrac{V_{(p)}}{\mathrm{SF}}$

since $\mathrm{Re} = \dfrac{\rho V L}{\mu}$

$$\mathrm{Re}_{(m)} = \mathrm{Re}_{(p)} \times \frac{1}{(\mathrm{SF})^2}$$

where

L = characteristic dimension

V = flow velocity

ρ = density

μ = dynamic viscosity

Re = Reynolds number

SF = scaling factor

Subscript 'p' denotes prototype variables

Subscript 'm' denotes model variables.

This affects the degree of turbulence and mixing within the model and will therefore tend to predict somewhat longer purge times than actually exist. This is borne out by the author's findings in full-scale boiler tests.

However, FWPP would accept that the tests in question are related to transient conditions, and the techniques used are reasonable in providing a qualitative indication; whereas normal studies for boiler design look in more detail at flows during steady-state conditions. FWPP is still somewhat doubtful that the modelling of the

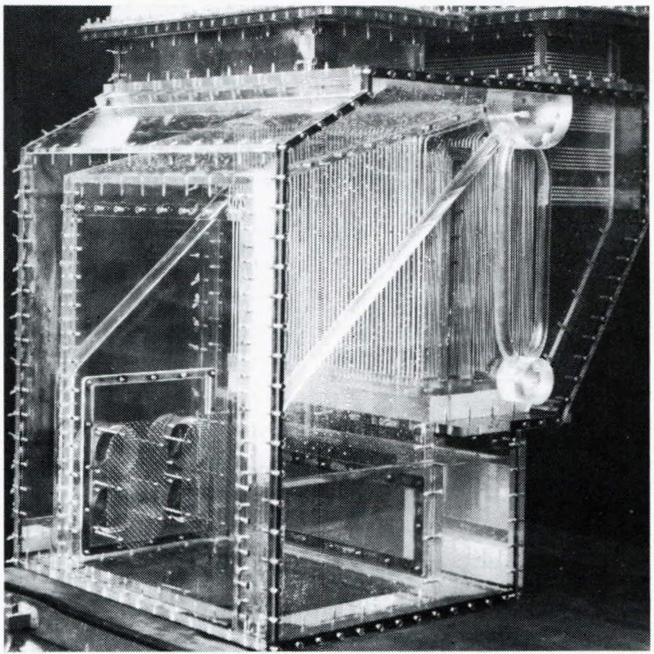


FIG D1 Typical marine boiler model

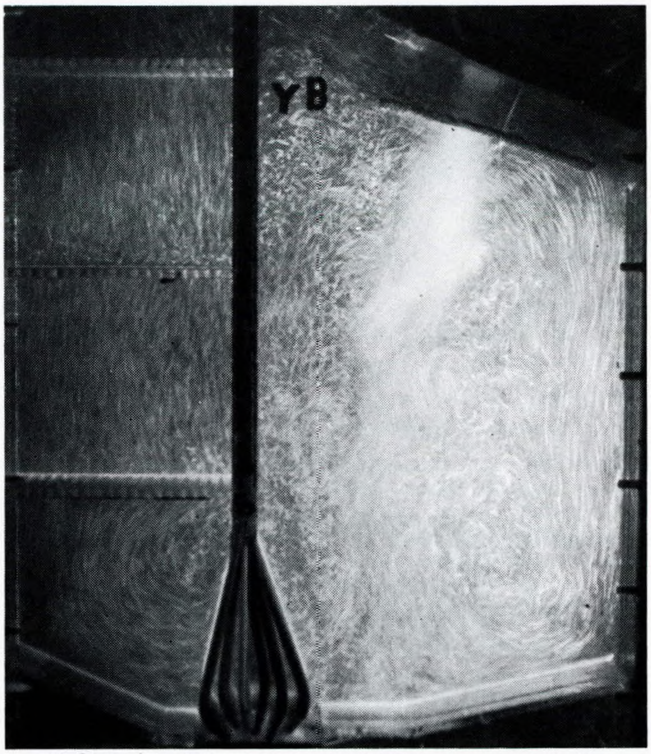


FIG D2 Typical flow patterns with ESD-type marine boiler

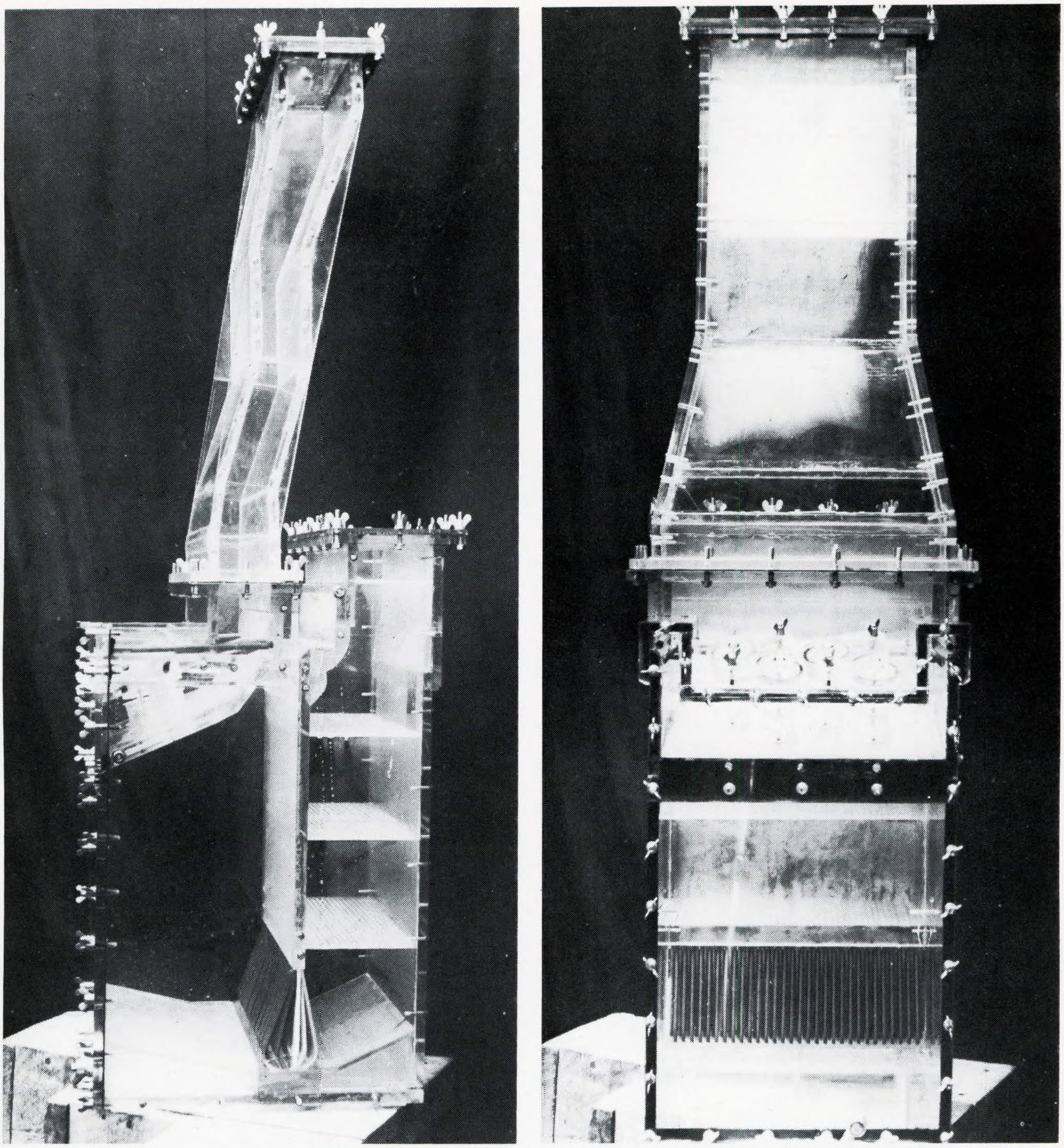


FIG D3 Three- and four-burner roof-fired ESD III boilers

burners is adequate in the tests reported, and would note that the normal practice of FW is to include swirlers and also, when modelling a boiler under operating conditions, to apply a gauze resistance at burner outlet to represent partly the rapid expansion effect of the flame-front (this technique is also used by the CEGB).

Figure D2 shows typical flow patterns within a marine boiler of the ESD type visualized using these techniques (cf. with published result).

FWPP also feels that the unrepresentative density difference between air and CO_2 in the model gas concentration test work may significantly affect the results in measured purging time.

It may also be of interest to report previous work carried out by FW on marine ESD boilers. In 1972, FWPP R & D Department undertook a series of flow studies on three- and four-burner, roof-fired ESD III boilers (Fig D3). The objectives of the tests were fourfold, as follows:

(i) to establish distributions between and around burners and to recommend vanes or baffles to correct any serious maldistributions;
(ii) to examine furnace flow patterns and determine whether these were acceptable;
(iii) to examine flow patterns in the outer casing from the air heater to windbox inlet;
(iv) to examine the furnace venting arrangements in relation to methane firing.

Flow visualisation tests were performed using water flows with entrained air tracers, whilst quantitative measurements of flow distributions were made using pitot-static probes and air flows. The results of these tests led to recommendations for several modifications to these particular boilers in order to prevent stratification of gas carried over from the air heater and to generally improve furnace flow distribution.

In general, FWPP feels that useful work has been done by these tests particularly with regard to the comparisons of model and full scale performances.

Even if doubting the preciseness of some of the modelling techniques, FWPP would agree the overall findings that the ESD III marine boiler design has no real purging problems. Experience on many hundreds of boilers in service confirms this.

Equally, FWPP has not been notified of any other significant problems of purging on auxiliary boilers but accept that if the detail design of the casing at main bank outlet is as per the particular licensee's design, a gas pocket could exist in the shielded area under certain conditions and various design arrangements can be used to overcome these problems as investigated by the author.

MR S.N. CLAYTON (Lloyd's Register of Shipping): Dr Dye's paper provides further valuable research into the factors leading to inadequate purging of furnaces and the resultant risk of explosion.

The serious nature of the problem in watertube boilers is well illustrated in Table DI which shows records from the Lloyd's Register classed fleet of incidents on steamships since 1975. These records are derived only from those incidents affecting main boilers considered worthy of reference as boiler explosions, and do not include minor blow-backs without consequential damage. Only in two of the recorded cases, one of which is described hereunder, was the explosion severe enough to cause serious damage or loss of life.

Although the sample size is small in statistical terms, there are several points of interest which may be extracted from the record. No particular manufacturer or type of boiler is disposed to explosion damage; structural similarity exists, however, in that the majority of these main boilers are roof fired and have membrane waterwalls.

From an operational standpoint the statistics would indicate that probably all recorded incidents occurred in port during unstable steaming conditions. It is relevant also to note that where details are available it would appear that a distillate fuel was being combusted or a change in type of fuel was being made.

It will be recalled that a major boiler explosion took place in Hamburg just over five years ago with the tragic loss of 28 lives. The explosion was in the combustion chamber space causing the membrane walls to be blown outwards, the top headers and risers being ruptured at the connection to the steam drum. The superheater banks and plain tube economisers were unaffected. The damage was consistent with the explosion having taken place in the upper part of the chamber which is shown by Fig. 3 in the paper as the last area to be purged.

This leads to certain other questions: namely, is the width of a chamber a contributory factor and how important is the spacing between burners? It is, of course, appreciated that second burners should be ignited and not flashed from a burner already in operation but the position of the air registers could, of themselves, lead to stagnant pockets of gas across the width of the furnace. It would be of interest to learn whether any attempt was made in the main boiler model testing to simulate conditions when only one or two registers were open.

I note the author's conclusion that purging at 100 per cent flow is preferable to purging at reduced rate for longer periods. In this connection it is known that an explosive mixture can form in the spaces in extremely short periods of time. Would the entry of the large volume of air give rise to danger where there were hot spots or incandescent deposits in the furnace or uptakes?

It is further noted that the author suggests that the relevant British Standard's requirements should be reconsidered. In this respect I would venture to suggest that other foreign standards should be reviewed since many are also incompatible. Some standards in fact recommend 5 min at not less than 25 per cent of total full-load volumetric air flow to give five air changes.

As a final comment, may I again revert to Table DI. It will be noted that many of the incidents appear to have occurred during manual operation of boilers. However, it must not be forgotten that, where the boilers are operated in the automated mode, a degraded logic system, which did not ensure purging for the correct duration and at the required rate, would, itself, produce risk of explosion.

MR D. WATSON (Babcock Power Ltd): It is agreed that, where model flow tests are used for estimating flow distribution and pressure drop under steady state conditions, both geometrical and dynamic similarity are required between the model and prototype—dynamic similarity being achieved by equality of Reynolds number. However, the visual display in the model and the corroborative data from the full scale tests make this paper a valuable contribution to the safe operation of marine boilers.

Table DI: Explosions in main WT Boilers between 1975–1980

BOILER DESIGN	DATE OF EXPLOSION	LOCATION: AT SEA/IN PORT	WELDED WALL	TOP FIRED	FUEL IN USE/ No. BURNERS LIT	AUTO/MANUAL CONTROL	DAMAGE TO PRESSURE PARTS
F.W. MSD	March 1975	In port	Yes	No front	Unknown	Unknown	None—casings damaged.
Comb.Eng. 2M8-WW	July 1975	In port	Yes	Yes	Diesel/1	Just switched to auto	Tube wall severely bent. Tubes fractured. Casing destroyed.
B&W MR2	Jan. 1976	In port fitting out	Yes	Yes	Diesel/2	Manual	All walls heavily bulged, two riser tubes sheared. Many ruptured wall tubes.
B&W MR2	April 1976	In port	Yes	Yes	Unknown/1	Unknown	Casing distorted. Membrane wall bulged.
F.W. EDSIII	Jan. 1977	At anchor	Yes	Yes	FO/diesel Reflashing	Manual	Casings, economisers and walls damaged.
F.W. ESD III	July 1977	In port	Yes	Yes	Changes from FO to diesel	Unknown	Side wall casing uptake distorted.
Kawasaki 2-drum	Dec. 1977	In port	Unknown	Unknown	FO	Manual	Economiser damaged.
Kawasaki UFG	Aug. 1978	Unknown	Yes	Yes	Unknown	Manual	Expansion joints fractured. Casing and membrane wall deformed.
Comb. Engr. V2.M8	Oct. 1980	In port	Unknown	Yes	Unknown	Unknown	Refractories destroyed. Casing buckled.
B&W M12	March 1978	In port	Unknown	Yes	Changed from diesel to FO	Manual	Upper and lower economiser banks damaged.

Perhaps it is opportune to give some reasons why a limited flow was initially proposed for furnace air purge.

1. To reduce the turbulence zone at the interface between purge air and possible rich gas mixture, so limiting the volume of mixture in the explosive range.
2. To reduce the possibility of higher air velocities causing random carbon particles deposited in the gas spaces to glow and thus provide a source of ignition.
3. To provide an acceptable flow for both purging and light-up without unnecessary repositioning of combustion control actuators thus increasing the time for light-off and providing additional functions which may cause maloperation.

In view of the necessity to modify the burner management functions to provide the time and flow levels mentioned in the paper, could the author or the oil company representative please give proposed modifications, bearing in mind the initial reasons for low flow purging.

It may be pertinent to state that during tests by CEGB on boilers at Isle of Grain, the 25 – 35 per cent flow rate was not adequate to purge the furnace and the rate had to be increased to 50 per cent. It is believed that this resulted in some modification to BS.799: Pt. 4 : 1972 where a purge rate of at least 50 per cent of the full-load air flow should be considered when the furnace is very large. It is assumed that the results of the CEGB tests at the Isle of Grain have been made public.

MR F.D. GAINEY (Shell Research Ltd.): During the latter half of 1978 and 1979, Shell Research carried out a series of purging trials on board two Shell tankers to ascertain the minimum safe purging times required to clear the boilers of any unburnt fuel-oil vapour following a flame failure or a failure to obtain ignition condition. This work complemented the more extensive model studies being carried out at the University of Manchester on behalf of Shell International Marine.

Dr Dye's paper described the experiments carried out on cold air flow, scale models of typical main and auxiliary boilers using both flow visualisation techniques and gas concentration measurements. These experiments showed that in the case of one particular auxiliary boiler design, a stable gas pocket formed, clearing only very slowly. Full-scale tests were then carried out on the actual boilers and, in general, these confirmed the findings of the model.

During the discussion of this paper, the author was asked to comment on the full-scale trials carried out, and on any further applications for the sulphur hexafluoride (SF_6) detection technique.

Full-scale studies

In the series of model studies carried out at the University of Manchester, carbon dioxide (CO_2) was used to represent unburnt fuel vapour throughout the gas concentration tests, with initial concentrations of 60 per cent vol. CO_2 typically being used. The vapour density of such a CO_2/air mixture was slightly greater than the accepted value for a fuel-oil vapour/air mixture, their densities relative to that of air being 1.3 and 1.2 respectively.

However, for the full-scale tests on board ship, the volumes of CO_2 required to achieve such concentrations would have been prohibitive. Consequently, a gas that could be detected in very low concentrations had to be chosen in order to reduce the volume of tracer gas to manageable quantities. Sulphur hexafluoride (SF_6), detectable in concentrations down to 1 part in 10^8, was readily available in mixtures of 10 per cent vol. SF_6 in nitrogen, the relative density with respect to air being 1.37. However, subsequent dilution by air to, typically, 4–20 ppM in the furnace/superheater sections during the full-scale trials reduces the relative density of the SF_6/nitrogen/air mixture to essentially 1.0.

Consequently, in the full-scale trials it was not possible to simulate accurately the effect on the purging characteristics of the difference in the densities of fuel-oil vapour and air, with the result that the purging times measured may be slightly shorter than in practice.

Similar problems to those found in the model work were experienced with the full-scale trials when the results were to be interpreted in terms of absolute explosive limits and hence purging times. Again, the initial concentration of the fuel vapour was unknown; thus it was difficult to define the degree to which the boiler must be purged to be below the explosive limit and hence safe.

Consequently, the results were analysed in terms of the time required to reduce the initial concentration to less than 5 per cent of the original maximum value. The inference of this is that, given the lower explosive limit for fuel oil is 1.5 per cent, the purging times obtained from the full-scale work are adequate to clear a boiler that has a fuel-oil vapour concentration of up to 30 per cent vol.

The full-scale purging trials using the SF_6 detection technique is one example of the situation where, perhaps, high concentrations of a particular gas in a large volume have to be represented by relatively low concentrations of a tracer gas in the same volume. Such a technique would also be useful in many other similar situations. Clearly, the use of SF_6 as a tracer gas to determine the purging time/characteristics of boilers is not restricted to oil-fired boilers as described in this paper. Similar trials could readily be conducted on gas- or coal-fired boilers.

Other applications in the field of boiler design would be the determination of gas residence times at various locations within furnace and superheater zones of a boiler. This would be particularly relevant for assessing the uniformity of heat flux distribution under various operating conditions. Similarly, the technique could be applied to quantifying/assessing changes in leakage rates of rotary combustion air pre-heaters.

A further application would be in the determination of ventilation rates and the effectiveness of forced ventilation. Specific examples of this could be the determination of the relative effectiveness of purging the cargo tanks of a crude or product carrier either with inert gas or with air, in gas freeing operations. Similarly the technique can be applied to determining areas of poor local ventilation rate resulting from obstructions, particularly in the case of cargo pump rooms.

Finally, there is the designed use of the equipment used in these tests, namely for the detection of leaks in a range of systems, from large pressure vessels to condensers in the steam systems.

MR R.G. BODDIE (FIMarE): All members of the Committee for BSI 799 1972 'Specification for oil burning equipment' have retired and it was not therefore possible to obtain comments on the paper which criticises the specification. However, a new committee will be formed shortly to revise the standard.

Clause 3.1.3, Operation 13, states 'Plant manufacturers should be consulted to determine the degree of purge necessary'. I understand this wording was included as the committee could not agree on the length of the purging time. I believe that the Admiralty have laid down a minimum purge time of 5 min. Apart from the risk of damage to the boiler there is also the navigational safety of the ship to be considered. Could the author say what length of purge time is acceptable to the Captain of the ship?

Could the author also say if the risk of a boiler explosion is more likely when burning a good quality fuel or a poor quality residual fuel, bearing in mind that the quality of the latter will continue to deteriorate in the future?

PROF. G. GROSSMANN (Technische Universität Berlin): This a very interesting paper on a highly important subject. Would the author please explain whether he took the temperature difference between the gas in the boiler and the purge air into account?

There are two kinds of dangerous situations. When a boiler in cold state misfires, there results a mixture of cold gases purged with cold air. Here the density of the gases and air is more or less equal. However, when the boiler is purged at service conditions, the gases inside the boiler are at 200 – 250°C, which means their density is nearly half of the density of the purge air. In this case the gas freeing of the upper part of the furnace (points 02 – 05 in Fig. 4) would take longer.

We have run similar model tests at Berlin, simulating the density differences with salt water and fresh water and adjusting the time and velocity scale according to Froude's law. A B&W-type boiler was taken as the model. Our results showed that 95 per cent of the gas in the dangerous area (point BM4 in Fig. 12) was cleared with three boiler volumes of air (the boiler volume is the whole volume of the furnace and the second pass), when the boiler was purged with a moderate flow. At full flow it took 3.5 – 4 volumes of air to clear the boiler.

Author's Reply

DR R.C.F. DYE: I would like to thank the contributors for the various comments made, many of which are most interesting. It is clear that the purging of boilers is a topic requiring further study and discussion.

I agree in general with Mr Turner's comments on Reynolds number similarity and the advantages of water models. Indeed, these points are mentioned in the paper. Further, I agree entirely with the view that flow visualisation is practically simpler in water. However, the air–gas mixture technique I used did allow gas concentrations to be measured (and automatically plotted) both simply and cheaply. Two other small points are that the effect of swirlers was investigated on the models, and in the purging condition it is not necessary to simulate gas expansion at the flame front.

In reply to Mr Clayton and Mr Watson, the main boiler model was designed so that purging on any number, or combination, of registers could be simulated. However, so far, comprehensive tests have only been made using all registers. My comment that full-flow purging appears to be advantageous is based on the efficiency of the process in terms of the air supply necessary. I agree with Mr Clayton and Mr Watson that there are possible dangers from incandescent deposits.

Mr Boddie's questions raised on the type of quality of fuel being combusted are interesting, but I do not feel competent to comment.

In answer to Professor Grosmann, the gas temperature was taken into account only in calculating the correct volumetric purge air flow (based on 120°C combustion air temperature).

(Further material, in answer to questions raised during the discussion of the paper which touched upon operational matters, was contributed by Mr K. Dohmel of Shell International Marine Ltd.)

MR K. DOHMEL: I should like to thank the author for his efforts to present this paper to the Institute and take the opportunity to answer some of the questions that are related to operational aspects of the boilers in question.

Referring to Mr Clayton's comments for main boilers, the purge air flow is automatically adjusted to 40–45 per cent of maximum air flow. The purge sequence is started as soon as the acceptance level of 40 per cent is reached. If, during the purge sequence, this air flow should fall below the acceptance level, the purging is aborted and has to be re-initiated prior to an ignition attempt. For auxiliary boilers a similar arrangement exists. However, the acceptance level for purging is set to 60 per cent and the boiler is purged at full air flow.

For both type of boilers, burners are individually ignited by inserting and energising the igniter. A confirmation signal that the igniter is energised and in the ignition position enables the fuel oil valve to be opened. The purge air flow, which determines the purge time, has been selected to achieve a balance between the risks involved of igniting combustible gas pockets by hot spots or incandescent deposits, and the time required to reinstate propulsive power following a loss of flame.

Mr Watson mentioned in his contribution that one of the reasons for low air flow purging was to simplify the burner management system to enable purging and igniting to be carried out at the same air flows. The main boiler is purged with all registers in the open position at 40 per cent maximum air flow. Ignition is done on one single burner with the other three air registers closed.

If 40 per cent total air flow is maintained through one register, this register would have a throughput of 160 per cent air flow of its design, at which a successful ignition is considered to be highly unlikely. On the vessels in question, different air flows are called upon by the burner management system for purging and ignition. The ignition air flow is set to 12.5 per cent total air flow, resulting in 50 per cent design air flow through one register. The setting was found to be most suitable for the ignition sequence.

Referring to Mr Boddie's question, Shell International Marine commissioned tests at the International Flame Research Foundation test facility at Ijmuiden (The Netherlands) to establish whether the 'fuels of the future' can be ignited and burned reliably. During the test, no difference between a straight-run heavy fuel and blends of various natures could be found. However, for all the fuels tested it became apparent that parameters such as oil flow, air flow and air temperature should be kept within certain levels to ensure successful ignition.

The purge time for the main boiler of 1–1.5 min is accepted by ships' Masters. However, modifications to hardware and operating procedures have been implemented to avoid the loss of flames. This is to eliminate the need for re-igniting the boiler, on occasions where the required purge time could be too long.

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