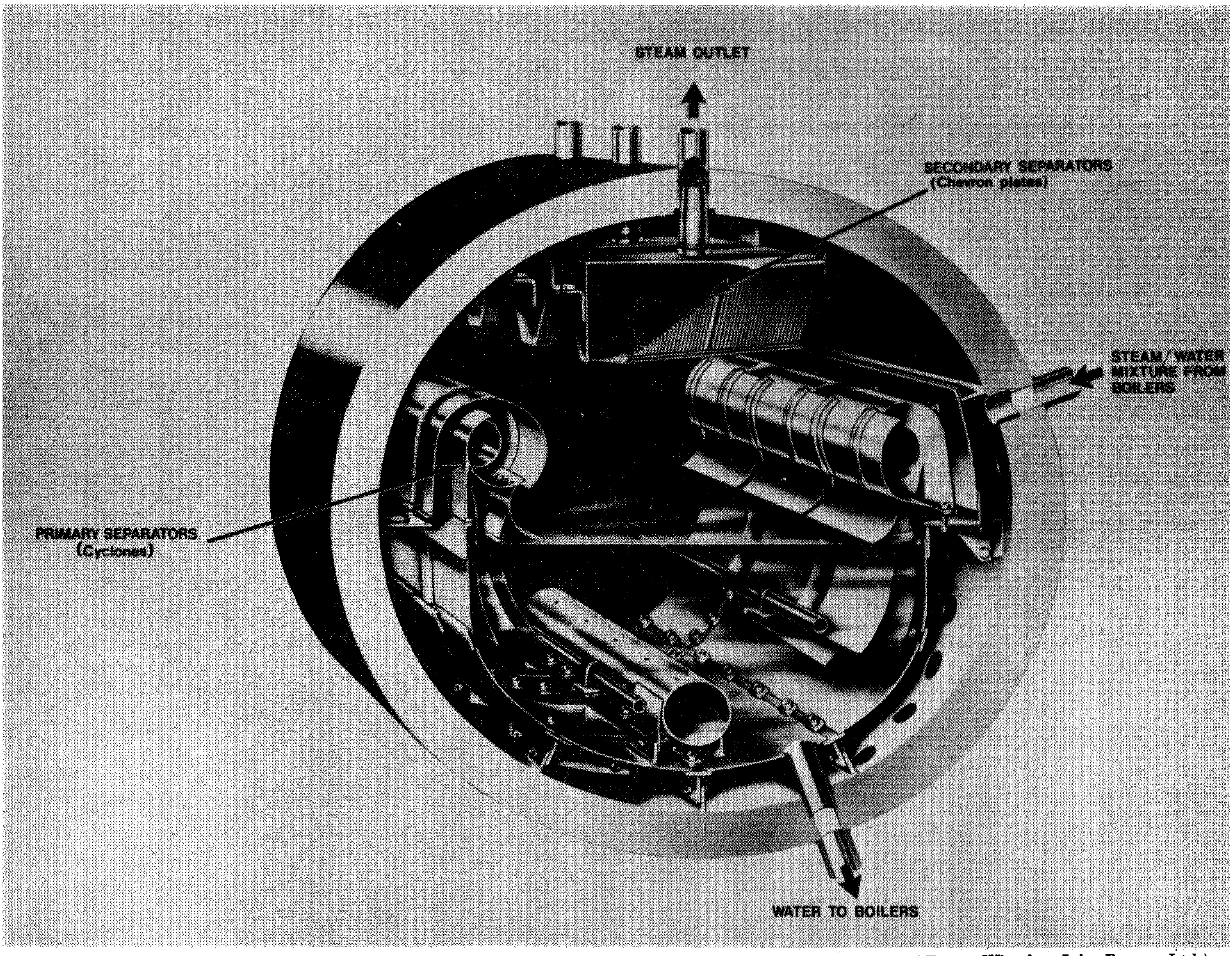


(Courtesy of Foster Wheeler/John Brown, Ltd.)

Figure 1. The internals of a steam drum designed to produce high quality steam.

Waste Heat Boilers: Problems & Solutions

A single failure of one of these units can easily result in a profit loss equal to the total cost of the boiler.

P. Hinchley, Imperial Chemical Industries, Ltd., Billingham, Teesside, England

It is a common practice in steam reforming plants to raise up to 300 ton/hr. of steam at pressures of around 1,500 lb./sq. in. gauge, and at temperatures of 480 to 525°C. The steam is usually generated from three sources: flue gas from the primary reformer; process gas, from the primary or secondary reformers and sometimes the high temperature shift and ammonia converters; and flue gas from auxiliary boiler burners whose firing rate is adjusted to produce the required total quantity of steam.

The boilers usually share a common steam drum. The water flows from the steam drum to the boiler by "natural" or "forced" circulation. For natural circulation the drum needs to be located some distance above the boilers to give sufficient driving force to the water and steam. The cost of the additional structure and piping partially offsets the cost of the circulating pumps.

Actual disengagement of the steam from the boiler water takes place in the steam drum, which normally has a water level at or near the center line. The steam usually has to pass through an internal separator to remove the entrained water before reaching the steam outlet pipe. Very high purity steam is required to prevent the deposition of solids in the superheater and turbine, and as a result the internals are rather complex as can be seen from Figure 1.

There is one interesting exception to this general pattern on an ammonia plant in Europe, which produces steam at 2,250 lb./sq. in. in a "once-through" type of boiler that does not have a steam drum. (*1*)

Flue gas boilers. Since flue gases are at or below atmospheric pressure, the high pressure steam is always generated inside the tubes of watertube boilers by passing the

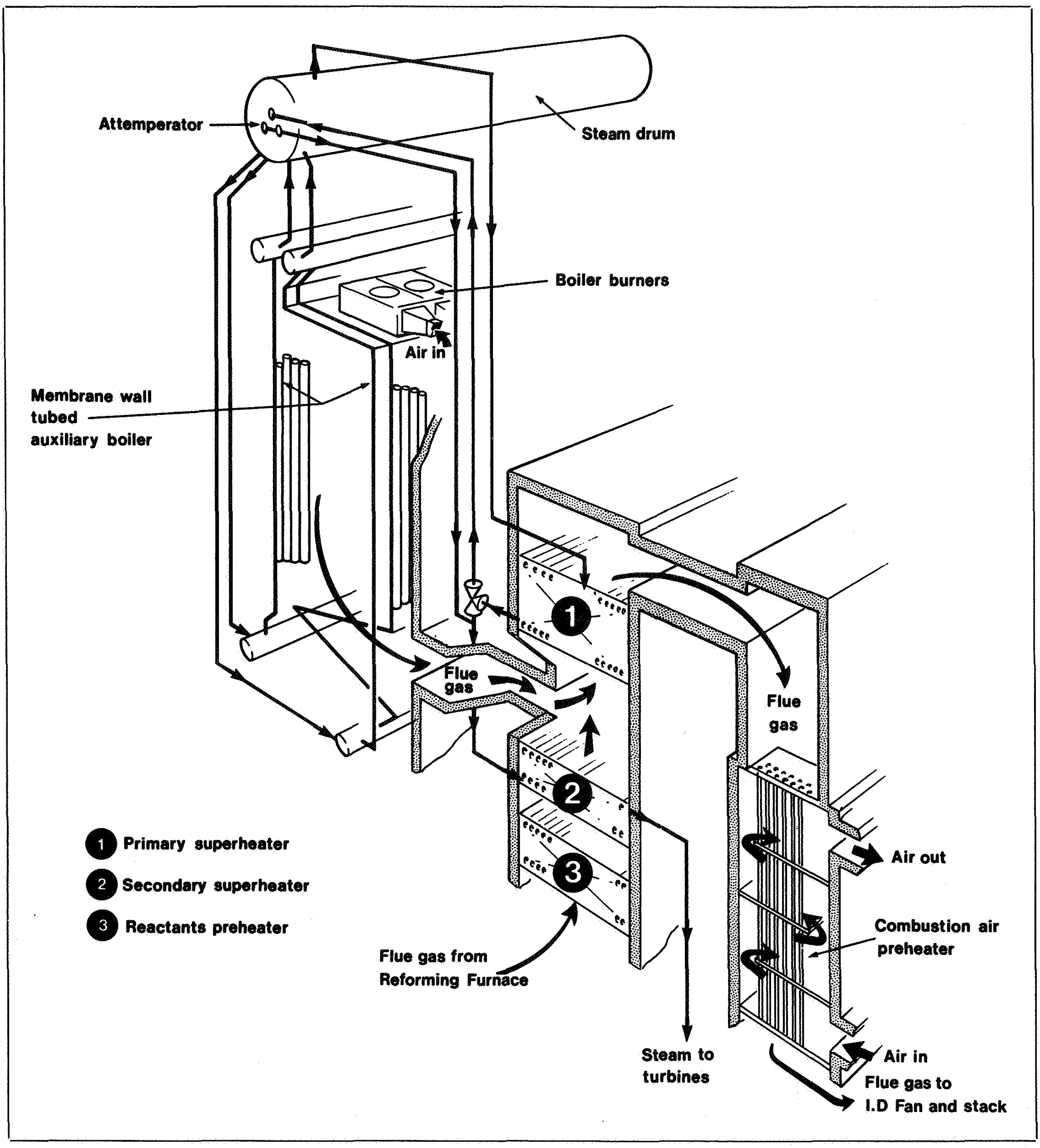


Figure 2. Vertical flue gas boiler in a reformer convection section.

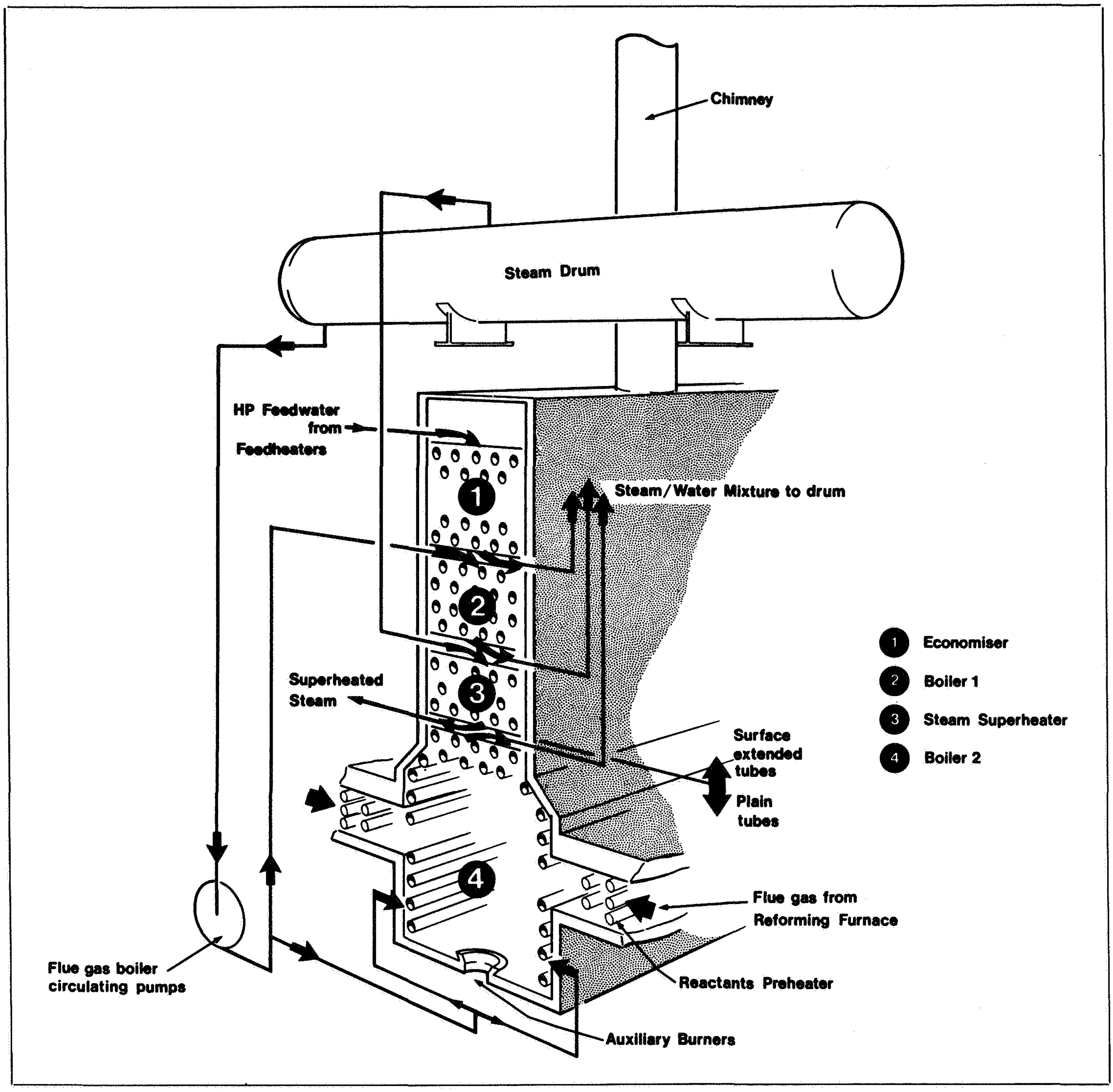


Figure 3. A horizontal forced circulation boiler that is heated by flue gas.

hot flue gases over them. If the boiler is designed by a boiler manufacturer, he will typically use 1 1/2 in. NB plain tubing, whereas a fired heater contractor is more likely to use 4 in. NB tubing, frequently with extended surface heat transfer fins. The boilers are of the vertical natural circulation type, Figure 2, or the more usual horizontal forced circulation type, Figure 3.

Process gas boilers. These fall into two categories, firetube and watertube. The principal features of a typical natural circulation firetube boiler on a reformer are shown in Figure 4. While several companies design and make such boilers there are significant differences among them with respect to maximum heat flux, maximum stream pressure, method of attaching the tubesheet to the shell and channel and of the tubes to the tubesheet, and method of protecting the tubesheet. The manufacturers also differ in their ability to carry out a sufficiently rigorous stress analysis, bearing in mind the high pressures involved and the differential expansion between tubes and shell.

To the best of my knowledge there are no 1,500 lb./sq. in. gauge firetube secondary reformer waste heat boilers operating in the U.S., but a number have been installed by European manufacturers.

The situation on watertube boilers is that a large number of companies have developed and patented their own designs. Some of them depend upon pumped circulation, but others work on natural circulation. Figure 5 shows one of the simpler designs, the vertical U-tube.

Troubleshooting techniques

Inevitably in a discussion of this nature it is necessary for completeness to describe failures that the author and others have previously dealt with in earlier papers. However, before doing so it is worth dwelling, in some detail, on a general problem that has received close attention in the more recent past and that is the question of "dry-out" in horizontal watertube boilers.

Failures have occurred on several boilers owing to a deep gouging corrosion at the 12 o'clock position, Figure 6. Experimental work has led to the conclusion that the problem has arisen because of the existence of a flow regime in part of tube where "dry-out" has occurred, i.e., where the wall is not continuously wetted. (*2*) In these "dry-out" zones any harmful chemicals can concentrate many thousand-fold and severe corrosion can occur if, say, there is free caustic in the boiler water. (*3, 4*)

Dry-out is a phenomenon known to the boiler industry because of the burn-out of vertical tubes in highly rated oil-fired boilers. There the heat fluxes are very much greater than those in the convection sections of reformers/heaters. The experimental work on vertical tubes has led people to believe that at the 20,000-B.t.u./sq. ft. heat flux level the steam quality would have to be of the order of 80% for dry-out to occur, whereas in practice it was occurring in horizontal tubes at less than 10% and much lower. The reasons for this difference is that the effect of gravity makes the film at the top of the tube much thinner than the film at the bottom. Flow experiments on unheated horizontal tubes show a ratio of thickness of 30:1.

Several cases of the problem having been identified, the questions then arise as to whether it can occur on the plants operating currently and how it can be avoided on new plants. The first thing that needs to be stated is that a boiler may well have been running for years with a dry-out situation and no ill-effects have occurred because the boiler water has been kept within specification. Provided this continues to be the case, no trouble should arise from the dry-out.

We experienced the failure of a 600 lb./sq. in. gauge flue gas boiler and were worried about it happening on a similar 1,000 lb./sq. in. gauge boiler that was being commissioned. In both cases we resorted to the use of a radioactive tracer, sodium 24, which enabled us to identify tube locations where concentration was taking place.

In the case of the former plant we were unable to avoid dry-out completely even though we doubled the water rate. However, we did improve the water quality and reduced the count rate. Additionally, we replaced the most vulnerable tubing in P9 (9% Cr, 1% Mo), which is more resistant to caustic attack.

We gave consideration to methods of avoiding dry-out by the use of devices to impart swirl to the water and keep the upper surface wetted. Ribbed or rifled bore tubing, as used in the boiler industry, could not be obtained in time for the plant shut down. We also considered the use of twisted tapes, but rejected this because of the dangers of crevice corrosion under the tapes and of chatter of the tape in the tube.

In the case of the new plant that was commissioned, the radioactive tracer technique enabled us to assess the effect of changing the operating conditions, and we eventually were able to adopt an operating mode in which no dry-out could be detected. The plant has since run for three years without the boiler failing although its water quality has always been subject to extra close scrutiny.

For new plants the position is not at all satisfactory. Very little experimental work has been done on dry-out in horizontal tubes and even that which has been done has been chiefly confined to 3/4 and 1 in. diameter tubing compared with the 4 in. diameter typically used on reformers and furnaces.

The typical comment from a heater vendor is that in order to avoid trouble they design for a high water velocity. This approach is highly suspect because there is a 1,500 lb./sq. in. gauge boiler that has suffered severe failures due to caustic corrosion brought on by dry-out in 4 in. NB tubes in which the water flow rate was very high, being 1.37 million lb./hr. sq. ft. (or 8 ft./sec. at inlet conditions). No doubt the problem was aggravated by the high heat flux

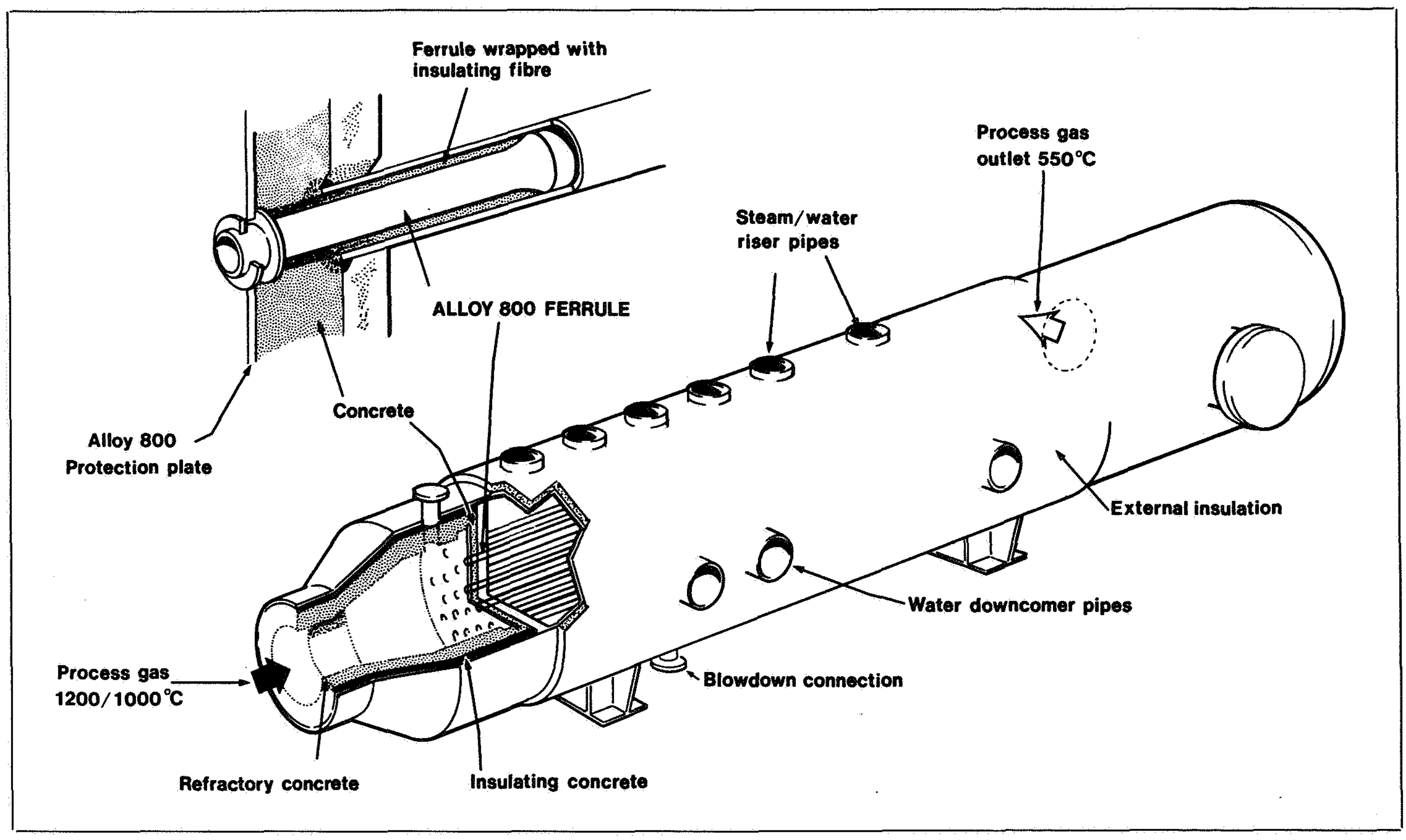


Figure 4. Reformer gas waste heat boiler showing principal features of typical natural circulation firetube boilers.

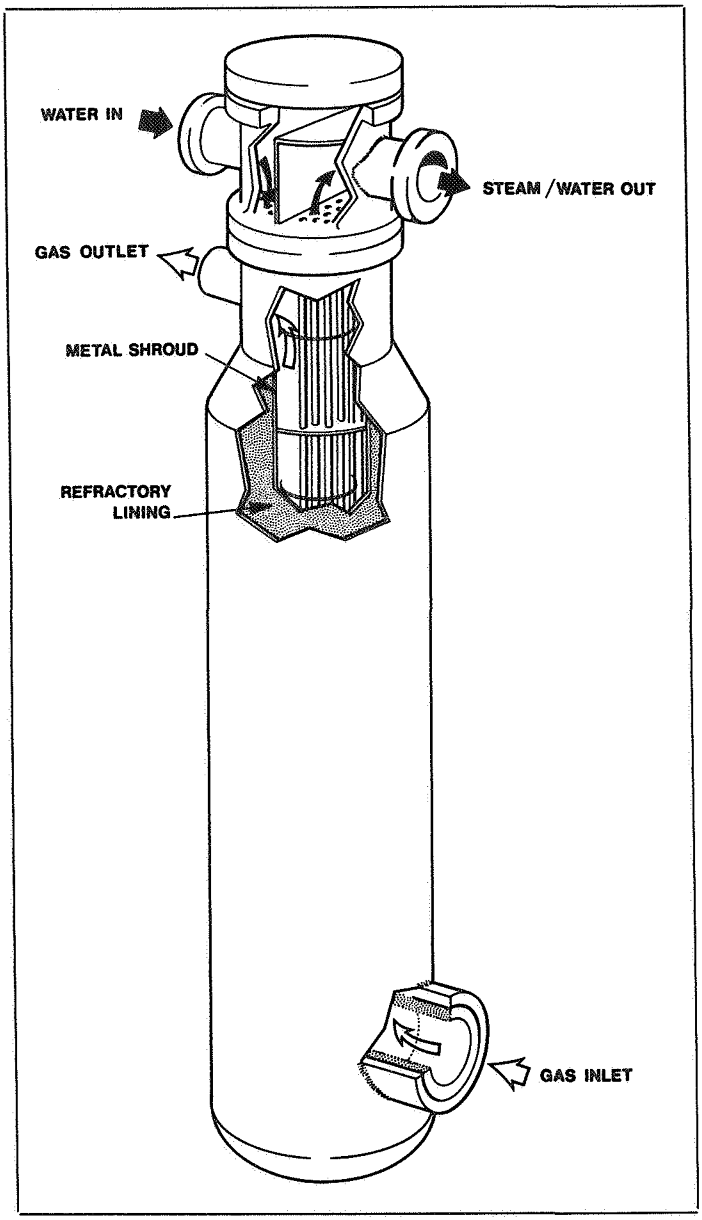


Figure 5. Reformed gas waste heat boiler arrangement of vertical U-tube water tube boiler.

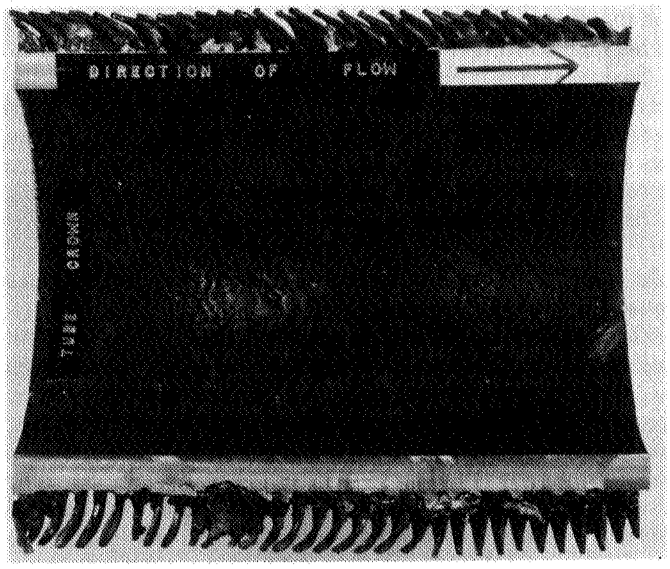


Figure 6. Tube of a horizontal flue gas boiler that failed as a result of severe corrosion in a region of dry-out.

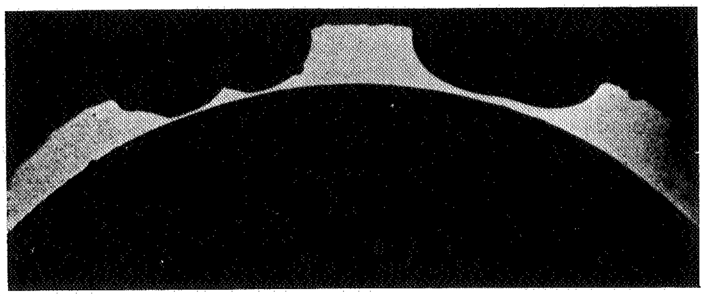


Figure 7. Water side corrosion of a fire tube boiler just beyond the end of the protective ferrule on the tube inlet.

of between 40,000 and 50,000 B.t.u./hr. sq. ft. arising from the use of extended surface tubing.

Failures and their causes

Flue gas heated boilers:

1. At least three boilers have failed as a result of caustic concentration due to the presence of free caustic and the existence of a dry-out zone in the horizontal 4 in. NB tubing. The solution in one case was to change to congruent phosphate treatment and thus ensure the absence of free caustic. (*5*)

In another case this was combined with a large increase in water rate and in a third case, where there was some doubt about the ability to avoid free caustic, 9% Cr 1% Mo tubes are to be used to replace the carbon steel tubes, some of which had only lasted three to five months.

2. Recently, a boiler tube on another reformer, which had been in operation for several years, ruptured violently without warning. Examination showed extensive corrosion, with deep gouging on the crown of several tubes and tram line corrosion/deposition on these and other tubes. The direction of gas flow was horizontal but the corrosion was on the top of the tubes.

Clearly, dry-out was occurring in the tubes, but in this case metallurgical examination indicated that a major contribution to this corrosion was attack by "acid chloride." It was found that there had been some slip of chloride from the mixed bed unit; and since the boiler operated on zero solids treatment, the trace of chloride had been able to concentrate in the dry-out regions.

The pass arrangement was changed so that the water velocity was doubled in the hope that this would prevent dry-out. Closer attention is being paid to the water treatment.

3. Several superheaters in reformer flue gas streams have failed by creep rupture as a result of carry over of boiler solids. The reasons include inadequate means of separating the steam from the water within the steam drum and mechanical failure due to overload of good quality primary and secondary separators. Another was caused by a badly made joint in a drum-type attemperator, which let boiler solids pass into the secondary superheater.

4. Some economizers have failed as a result of oxygen

pitting. Careful and thorough checking, using stainless steel sample lines, has shown that many proprietary deaerators fail to achieve their specified duties. A contributory reason in a number of cases has been that the temperature of feedwater and/or the condensate entering the deaerator has been higher than specified to the vendor, and as a result less steam is available for scrubbing out the oxygen.

5. A rupture occurred in the upper outlet row of a steaming economizer shortly after a massive breakthrough of acid from the demineralization plant. This outlet row was heated by the hottest flue gas from the reformer, which flowed down past the bundle. Separation of the steam and water phases was apparent from the corrosion tramlines and the failure was by deep corrosion at the crown of the tube.

Process gas heated firetube boilers:

1. At least three boilers have suffered severe corrosion on the water side of the tubes just beyond the end of the protective ferrules at the tube inlets, Figure 7. It has been caused by acidic or free caustic conditions in the boiler water. In two cases the aggressive corrosion had taken place below deposits that were themselves corrosion products originating from upstream equipment that suffered corrosion because of poor deaeration of the feedwater. Naturally, those boilers with the highest heat flux or poorest water distribution, or both, are most prone to failure should the boiler water quality deviate from the optimum.

2. Frequent leakage occurred on some boilers because of circumferential cracks of the tubes within the cold-end tubesheets. The cracks started from the outside of the tube, either at the root or heat-affected zone of the tube-to-tubeplate weld. After extensive investigations, it was concluded that the problem lay in the design of the boiler rather than in its operation and new boilers of improved design were installed. (*6*)

3. Tubes and tubesheet have failed as a result of overheating due to the build-up of boiler solids behind the tubesheet. This has occurred on several boilers and has been caused either by an inadequate blowdown provision in the design, or by the failure to use that which has been provided. The risk with a vertical boiler is clearly greater than with a horizontal one, since its bottom tubesheet is the low point in the boiler.

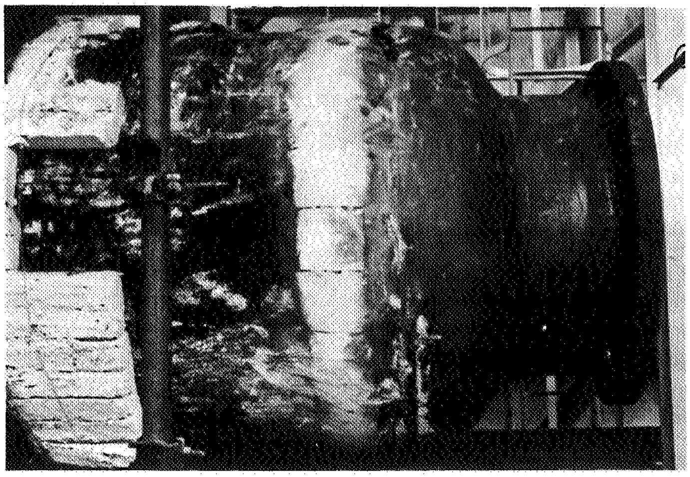
4. The gas channels of several boilers have swollen as a result of gross overheating when external insulation on the shell containing the water has been extended on to the refractory lined channel containing the gas, or when there has been a failure of the internal refractory lining, Figure 8.

5. Another problem involved overheating of tubes within a tubesheet as a result of using a thick tubesheet, inadequately protected by the ferrules in the tube ends. There were two stages in solving the problem. The first was to improve the insulation by increasing the gap between tube and ferrule and filling it with ceramic fiber paper. The second stage was to prevent gas tracking by tapering the outlet of the ferrule and machining its end to ensure a good fit in the tube bore at operation condition (see detail in Figure 5).

6. Failures of a main shell-to-tubesheet weld, in one case during hydrostatic test, and in the other after several months operation, were both due to a combination of unsatisfactory design, poor workmanship and inadequate quality control.

Process gas heated watertube boilers

It is not possible to go into the same amount of detail on water tube boilers because considerations of commercial secrecy prevent the public display of the relevant details of proprietary designs. Nevertheless, in order to present a balanced picture, an attempt will be made to indicate the



▲Figure 8. Swollen inlet channel of a fire tube boiler caused by gross overheating when the external insulation of the shell was mistakenly extended over a channel containing hot gas, and which was lined internally with refractory material.

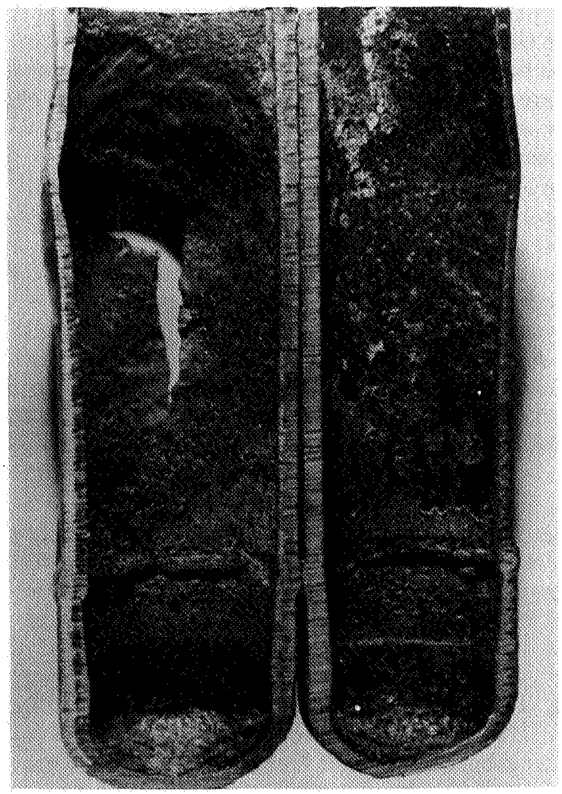


Figure 9. Section through the scabbard tube of a bayonet tube boiler that failed as a result of corrosion and overheating arising from water side problems.

reasons for the many failures that have occurred.

1. Creep rupture of individual tubes arising from overheating due to restriction in flow caused by a partial or complete blockage of the tube inlet. The blockages have been caused by such things as fabrication, construction and maintenance debris, and by magnetite scale dislodged during plant upsets.

2. Rapid corrosion of tubes following massive acid breakthrough from the water treatment plant.

3. Corrosion of tubes caused by the concentration of harmful chemicals in the boiler water, beneath deposits existing in the regions of the tubes subject to the highest heat flux. Frequent contributors to this problem have been contaminated return condensate and the breakthrough of acid or alkali with the feedwater, Figure 9.

4. Creep-rupture of the gas pressure shell because of the failure of the refractory lining, the latter usually being due to a combination of poor design, workmanship, and quality control.

5. Frequent creep rupture of the tubes in a horizontal U-tube boiler handling the 980°C gas from a secondary reformer. The failures were at the top of the tubes and were caused by dry-out. The problem was eventually solved by increasing the water rate, changing to a higher grade of tubing and fitting twisted tapes to ensure that the upper surfaces of tubes were constantly wetted.

6. Leaks in a similar boiler handling the much cooler gas from the high temperature shift converter. The failures were also at the top of the tubes but the mechanism was somewhat different. It was corrosion due to the concentration of harmful chemicals in a dry-out zone. The problem was overcome by increasing the water circulation rate to avoid dry-out.

Water quality

It is clear from the foregoing that the quality of the water fed to the boilers has frequently been a major contributory factor to many of the failures. Obviously it is necessary to provide adequate water treatment facilities but even then, experience in many locations has shown it is not uncommon for acid or alkali breakthrough to occur. A frequent cause is the failure to carry out an adequate final rinse at the end of the regeneration cycle of any of the ion exchange units.

There is some evidence to show that the risk of breakthrough is greater with manually operated plants, and for this reason automated plants are preferred. In either case it is strongly recommended that the water leaving the demineralization plant has its conductivity constantly measured and that an automatic trip be actuated if it reaches a pre-set level. This trip can either dump the water to drain or trip the transfer pump, thus ensuring that contaminated water never enters the demineralized water storage tank. Clearly, the larger this tank, the more time there is to identify and rectify the fault.

Another common problem is the contamination of the steam condensate, by cooling water, as a result of leakage in the vacuum condensers. The conductivity of this and other return condensates should be continuously monitored; if contamination is detected then the only safe thing to do is to dump the affected condensate. On some sites the water balance is such that the plant cannot run without the vacuum condensate. On one such site, where the cooling tower make-up is sea water, the link between bayonet tube boiler failures and vacuum condensate contamination is considered to be so strong that if a high conductivity is confirmed, the plant is taken off "make" and brought down to the point where it can operate without the condensate, while the necessary repairs are made to the condenser.

The method of treatment of the boiler water is a matter for specialists, however, a method and bogey figures having been selected, it is vital that they are understood by the operators and that the key readings such as pH, conductivity, and phosphate level are constantly monitored from the control room.

Which is best?

It is not possible to recommend one waste heat boiler over another, but the following points should be remembered.

Flue gas boilers. Vertical natural-circulation boilers are intrinsically more reliable than forced-circulation horizontal boilers. Nevertheless, the vast majority of horizontal boilers are reliable but there is a potential risk of dry-out, which can cause severe corrosion if harmful chemicals are present in the boiler water.

Insufficient data exist on the conditions that cause dry-out, so that it is not easy to be certain at the design stage that it will not occur in horizontal boilers. With vertical waste heat boilers there is little risk of dry-out, because the critical heat flux is many times greater than in horizontal boilers.

Process gas boilers. Provided the design and fabrication are to high enough standards, horizontal natural circulation firetube boilers are basically more reliable than forced circulation watertube boilers. The latter are prone to failure if dirt or debris gets into the system, particularly with vertical boilers, which have their low point in the area of highest temperature and heat flux.

However, boiler water problems can give rise to failures of either type of boiler; and if a large number of tubes fail, a spare water tube bundle can be fitted in a relatively short time, whereas a firetube boiler requires a very long time to retube or replace. Such major failures are rare and when only a few tubes are affected they can be readily plugged off.

A decision might be made to adopt a watertube design. In that case, in addition to the bayonet and U-tube boilers commonly used in North America, there are available from European vendors at least five proprietary types that are operating in various parts of the world. Advantages and disadvantages exist in every type. The choice for a particular plant should be based on an objective assessment of these factors in the context of the plant location, the experience of other users, and on the price quoted. #

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P. Hinchley, who graduated with first class honors in mechanical engineering from Sheffield Univ., England, has been working for the Agricultural Div. of ICI for the past 21 years where he has been involved in engineering research, process investigation, plant maintenance, equipment design, and project engineering and management. The holder of two patents, he is currently manager, of the division's Furnace and Boiler Section.

DISCUSSION

JAN BLANKEN, UKF, Holland: I understand from your excellent paper that you have had problems with your 102C Secondary Waste Heat Boilers. We have had corrosion, in one of our 102C boilers, at the outside of the tubes, above the bottom tube sheet. It was as if beavers had eaten away the metal. Could I ask what you have done to avoid the problem.

HINCHLEY: First of all I would like to make the point that the paper is a world-wide review. I would not like you to go away with the thought that ICI has experienced all these problems. The information given in the paper was provided on the understanding that I did not disclose its source.

The boiler that you refer to was of the vertical firetube type and failures occurred by overheating and corrosion of the outside of the tubes caused by the buildup of solids on the bottom tubesheet. This was a low point in the system and the blowdown facilities were inadequate. It was known that the latest design of such boilers incorporated changes that improve the blowdown facilities and also direct the incoming feedwater across the tubesheet. Nevertheless, it was decided to make a more fundamental approach and install horizontal boilers with vertical tube sheets. The solids and any debris entering such boilers tend to fall to the bottom of the boiler where they cannot do much harm since there is usually an annular space between the tubes and the shell. Buildup is prevented by the use of blowdown connections adjacent to the tubesheets. The new horizontal boilers have operated satisfactorily and have overcome the problems on that plant.

In my opinion firetube boilers should always be installed horizontally, rather than vertically, unless there are very special reasons for not doing this on a particular plant. There is no point in "fighting nature" unnecessarily.

M. BADREL DIN, Petrochemical Industries Co., Kuwait: There is one development which we heard about and I wonder how widely it is accepted nowadays, i.e., splitting the horizontal firetube Secondary Reformer Boiler into two, with a hot section and a cooler one.

HINCHLEY: The answer to your question is that there is an increasing tendency to adopt this approach on high pressure firetube boilers on ammonia plants. There are two reasons for doing this. If one makes a reasonably conservative allowance for gas side fouling, then the required length of tube will be about 30 to 35 ft. Such a length produces large stresses due to the differential expansion between tube and shell and failures have occurred on some high pressure boilers because of this. The second reason is connected with the need to control the temperature going forward into the HT Shift Converter. This can be done by either an internal or an external gas bypass valve. In either case the duty of the bypass system is made easier if the bypass is taken after all the gas has been cooled by passage through the hot section of the boiler.

DIN: I have another question regarding this blowdown connection on the bottom that you seem to place some value on. We had one and a couple of years ago we reported a major failure which was caused by someone accidentally failing to shut off this blowdown resulting in a loss of water level in the drum. So we have stopped using the lower blowdown. We think that the continuous blowdown from the drum should be adequate providing the water quality is OK but would welcome your observations.

HINCHLEY: I suggest that at your next shut down you disconnect the blowdown pipe and inspect the inside of the boiler to see if there is evidence of any buildup of solids or debris. We have brought our curved blowdown pipe through a flanged blank in the base of the boilers adjacent to each tubesheet and at a routine overhaul we remove the flanged connection to confirm that there is no solids buildup and, at the same time, we check the condition of the tubes in this potentially vulnerable area of the boiler. Colored photographs can be used as a basis of comparison with previous inspections.

HINCHLEY: If there are no more questions I would like to mention a Secondary Reformer Boiler which is outstandingly different. It is installed on a 1000 Tonne/Day Ammonia Plant in France and raises steam at 150 atmospheres or 2250 lb./sq.in. in a "mono-tube" boiler described in detail in reference 1. It does not have a steam drum, nor risers or downcomers, nor circulating pumps. The primary and secondary boilers complete with temperature controlled bypass are all in a single vertical shell close coupled to the Secondary Reformer. The boiler has operated for 5 yr. without trouble. I have mentioned this boiler because of its technical interest and not because I think that it is basically more reliable than other types of boiler. I think that the standards of that particular operating company were such that they would have had equally trouble-free operation with many other types of boiler.