HMS FEARLESS
RESTORING CONFIDENCE

BY

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ABSTRACT

This article presents the investigation and confidence building process embarked upon following the discovery of cracks in the After Machinery Space boiler of the Assault Ship HMS *Fearless*. The actions taken to repair the boiler, and to justify further safe operational steaming up to, and including the 1,000 hour inspection conducted at Marmaris, Turkey in mid September 2001, and the audit trail for the decisions taken are included. It is not intended to dwell on the detailed metallurgical analysis, or on the techniques of the individual repair processes – which, in the main are well proven and have been reported elsewhere.

Background

HMS *Fearless* is the last steam propelled surface ship in the Royal Navy, having first been commissioned in the mid 1960's. The boilers were constructed by Babcock & Wilcox, now part of Mitsui Babcock, with a design life of around 35 years. However, delays incurred in the construction of *Fearless*'s successor have necessitated her being run on until early 2003 – a feat in itself requiring much revalidation work and additional testing.

In November 2000 *Fearless* suffered a fire on the lower level of the After Machinery Space (AMS). Although the correct emergency action to 'crash-stop' ventilation and shut down the AMS boiler was taken, a concurrent failure of a fuel system cut-off valve, and a siphoning effect from the thereby non-isolable on-line fuel tank prevented the boiler flame from being extinguished, allowing a secondary fire to continue on the furnace floor. The AMS was steam drenched, suffocating the originating fire, but Ship's Staff had to resort to directing seawater down the funnel to extinguish the fire within the furnace. It was subsequently found that the furnace was flooded to a depth of approximately 0.5m. A visual inspection in Malta and a second, more detailed, survey conducted on return to Portsmouth, revealed significant boiler tube distortion and a repair programme of refurbishment and tube replacement was implemented over the next few months. A general view of the AMS boiler is provided at (FIG.1).

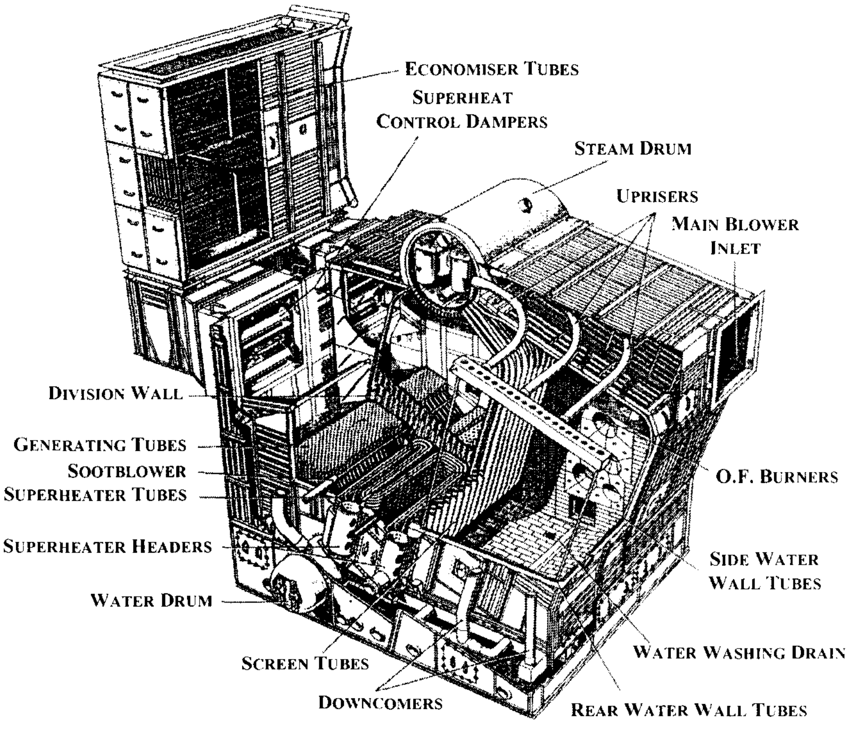

FIG.1 – GENERAL VIEW OF AMS BOILER

The following May, a post repair hydro test to 1.1x Working Pressure (WP) of the AMS boiler water drum revealed a leak around tube G14. With the tube removed a through wall crack was found extending for about 24mm into the base metal of the tube plate. Temporarily neglecting the fire and because the cause of cracking in the after boiler water drum was not immediately obvious, and as the same circumstances might also apply to the steam drum and the Forward Machinery Space (FMS) boiler drums, the Authority to Operate (ATO) for both the AMS and FMS boilers was revoked.

A full and extensive NDE programme for both the FMS and AMS boilers was implemented, including Magnetic Particle Inspection (MPI), hardness surveys and metallographic examination of the cracks. These detailed inspections revealed three more cracks in the water drum, by MPI, and a fifth crack in the steam drum by a chance visual check.

Scoping the problem

The extent of the defects presented the MoD with a unique problem. On the one hand, there was a clear need to repair *Fearless*, re-issue her ATO and allow her to sail for essential Royal Marines amphibious training. On the other hand, there was little confidence that the 35 year old boiler was not suffering from age/fatigue and was terminally damaged, that no further cracks would develop or indeed that all the cracks had been found. In particular, the failure of the 'standard' NDE technique of MPI to detect the crack at steam drum hole C6 (8mm long and located during a visual inspection (see below)) was deemed particularly worrying. This seemed to further undermine confidence in the results from the last, and identical, NDE inspection conducted in the FMS boiler. Furthermore, the slow run down of the population of steam experienced personnel in the Royal Navy and the Naval Bases, which had gathered pace throughout the 1990's, further weakened the available knowledge and challenged the concept of 'having a competent steam Design Authority.' This, against the background of Health and Safety and Pressurised Systems regulations further steepened the hill ahead of the MoD. In short, confidence in the MoD's understanding of the causes behind the problem, and their ability to counteract and overcome them, was low.

First Steps

From the beginning, it was realised that it would not be possible to immediately restore a full ATO, and that an iterative process would have to be followed. Hopefully this would allow restoration of a 5,000 hour ATO (from first flash, post repair) in time to allow an important scheduled training exercise to be completed between August and December 2001. Given the enormity of the problem, the potential consequences of incorrect analysis and the lack of in-house expertise, it was decided, to pool all available experience, drawing on industry and other authorities such as DERA (now QinetiQ) and Lloyds Register, and to form a 'virtual' combined project team. The key aim of this team was to ensure that:

- All possible considerations had been taken into account.
- All potential causes had been fully investigated.
- Independent assessments of all available information had been gathered so that:

  > 'all risks were reduced to, and maintained at a level that is
  > As Low As Reasonably Practical (ALARP).'
- The investigative process itself was mapped out as a live document, thereby ensuring that an auditable trail was available at all stages of the recovery process.

As a further confidence measure, a 'Peer Group Review' forum was instigated to crosscheck that the project team had taken all available information sources into account, and had reacted correctly to them.

In the event, it was only necessary for the process used by the MoD project team to be 'peer-reviewed' twice, once on completion of the initial investigation and again when it was thought that sufficient confidence existed in the understanding of the cracking mechanism and recovery options to allow a way ahead to be proposed. On both occasions the Peer Group were able to endorse the project teams' decisions and the recovery process was able to advance. The entire process is shown at Annex A.

The Investigation

The findings of the initial investigation concluded that:

(*a*) The fire was not responsible for the cracking discovered in the AMS water and steam drums. This was based on the relatively low temperatures likely to have been encountered from the sub-optimal fuel combustion, which would have occurred when boiler ventilation was crash-stopped. Equally, the quenching of the hot boiler tubes and water drum, which would have occurred when seawater was directed down the funnel, was also dismissed as unlikely to have caused the cracking. This was on account of the considerable amount of flash-off, which would have occurred en route in the hot funnel uptakes.

(*b*) The original crack at G14 had propagated 24mm along the internal wall of the water drum and had penetrated through the 38mm thick ducol steel, resulting in a 7mm crack along the furnace side of the tube plate. A further three cracks, between 1 and 5mm long were found in the water drum around tube SR2. An additional 8mm crack in the AMS steam drum at tube hole C6 was discovered during tube replacement in an area previously declared clear of cracks. None of these latter cracks were through-wall, and no cracks were discovered in the FMS boiler.

(*c*) All cracks appeared to be associated with 'half-moon' shaped regions of potentially Martensite[♣] areas, each bordering a segment of a tube hole's circumference. It was assumed that these cracks had been generated by heating with an oxy-acetylene torch during the tube removal process, followed by a 'quenching effect' from the surrounding and relatively cool steel. Furthermore, all cracks originated from the 1.5 or 2 inch tubes and none originated from the 1inch tubes. The presence of Martensite was subsequently confirmed by conducting hardness checks around each potential site.[♣♣]

(*d*) A total of 37 tubes had been replaced in the AMS boiler during the Contract Support Period in the year 2000 (CSP00). In each case, it became clear that the outgoing tube had been cut out using an oxy-acetylene torch. Of these, 2 tube-holes, G14 and SR2, had cracks.

(*e*) Ninety tubes were removed in May 2001 to allow repair of the G14 tube hole. Although these tubes were not removed by oxy-acetylene equipment, the presence of Martensite around 87 of the tube holes confirmed that this process had been used in the past. These 90 tubes included all of those that had been replaced in CSP00. Access to SR2, and steam drum tube C6, was possible without further tube removal.

(*f*) In accordance with standard practice, the tube replacement process involved mechanical re-rolling (plastic deformation of the tube

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[♣] Martensite – an unstable tetragonal lattice structure formed when cooling (quenching) Austenite to Ferrite.
Note: Iron is Allotropic. Body Centered Cubic (B.C.C.) and/or Face Centered Cubic (F.C.C.) at different temperatures.

[♣♣] Although not a precise science, for the purpose of this investigation, readings of >400 were taken to indicate the presence of Martensite, whereas the parent metal had typical readings in the 180-250 range.

material and elastic deformation of the ligament plate to ensure a watertight seal). It was surmized that the stresses introduced by the rolling process itself were responsible for causing the brittle Martensitic regions to crack.

(g) The cracks at ligament holes G14 and SR2 were cut out and subjected to analysis by Mitsui Babcock, Lloyds Register and DERA, (FIG.2). This group also concluded that the tube rolling had imposed high tensile stresses on the ligament hole walls, which may have caused the formation of small cracks in the heat affected zones, and that these cracks had subsequently grown by a Stress Corrosion Cracking (SCC) process. They also concluded that the residual ligament stress alone was sufficient to cause SCC, although, in their opinion, they thought that crack propagation by this method was unlikely without the existence of an initiating crack or surface defect.♣♣♣

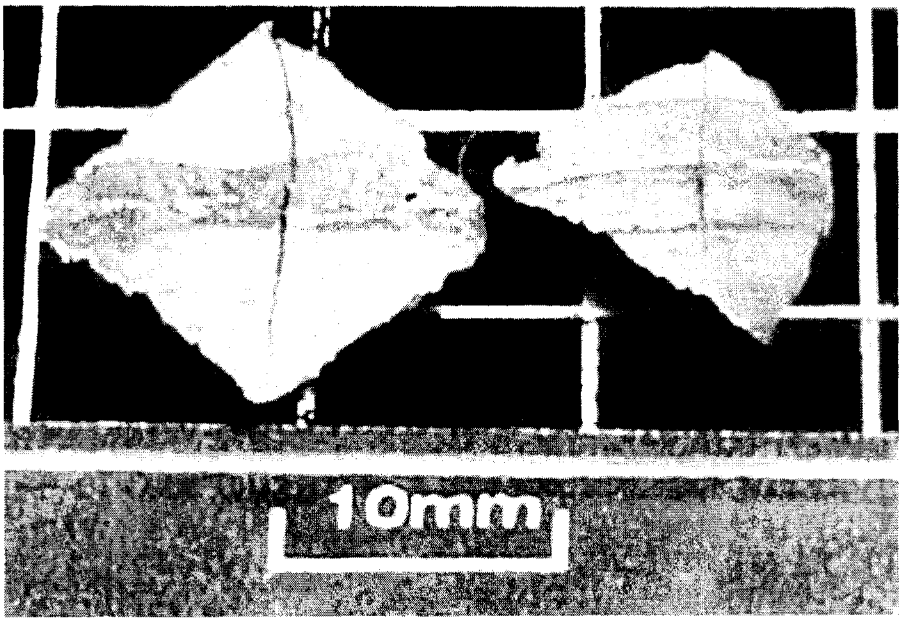


FIG.2 – CRACKS CUT OUT FROM AMS WATER DRUM SR2 TUBE PLATE LIGAMENT

(*h*) A literature search for other incidences of boiler cracking was largely negative in that there was no historical evidence of ligament cracking in either boiler water or steam drums, originating from an SCC mechanism, which had resulted in a catastrophic failure.

(*i*) Verbal consultations with many retired boiler operators and maintainers were undertaken. Although a few other avenues of investigation were followed, for various reasons, none were found to be similar to the circumstances pertinent to *Fearless.*

Understanding the Cause

♣♣♣ The role of Lloyds Register and subsequently Rolls-Royce, was to provide an independent check of Mitsui Babcock and DERA's conclusions; their inclusion led to considerable debate and challenge to the original diagnosis.

From the above, and in the absence of any evidence to the contrary, investigation centred on the tube removal process by oxy-acetylene cutting. Further investigations with Base staff – some of whom were contacted in their retirement – revealed that this process had definitely not been employed prior to 1998, the point at which the responsibility for boiler repairs had passed from MoD/FMRO Base staff to contractors. Before this point, all tubes had been cold-removed with boilermakers chisels. This conclusion was supported by:

(*a*) *Fearless*'s sister ship, *Intrepid*, de-commissioned and laid up in the Reserve Fleet, was subsequently found to have no Martensite precursors in her AMS boiler. *Intrepid* had not had any boiler work conducted since 1998.

(*b*) The 1 inch tubes were too small to allow insertion of an oxy-acetylene cutting tool, thus explaining why these tubes were devoid of Martensite or cracks.

Whereas tube-rolling has always been the standard way of 'bedding in' replacement tubes, this process had not previously been undertaken in a martensitic environment. As a consequence, the likely effect was unknown - explaining the negative results from the literature survey. Investigations also revealed that tube rolling was an art conducted solely 'by rule of thumb' and previous experience and that no Engineering Procedure existed. In effect, this meant that there was no control or record of the degree of stressing to which each tube and its corresponding ligament had been subjected. This was of particular concern as it subsequently came to light that some tubes, which had leaked on the first pressure test, had been re-rolled and re-tested – sometimes on up to 7 or 8 occasions. The repeated pressure-cycling of the boiler drum itself during the associated testing was also noted as a potential concern and instructions issued that 1.5 x strength tests were only to be conducted immediately after a physical alteration (e.g.: a weld repair) had been conducted; a 1.1 x Working Pressure test otherwise sufficing for leak checking. This brought the Management of the Boiler Repair process into line with BS1113 (as expected by the Pressurised System's Safety Regulations code of practice).

The above analysis however, did not explain the existence of the 24mm crack at water drum ligament hole G14. In the majority of cases, the Martensitic layer around the affected tube holes was around 5-8mm (with a single exception of 14mm at one hole). This was in most cases confined to the waterside of the boiler, although small amounts of Martensite were also apparent on the furnace side of the boiler shell at some ligament holes. The clear extension of the crack at G14 into the parent metal implied that either the rolling process had, in this case, been sufficiently large to crack the relatively ductile parent metal (unlikely), or that a different mechanism had existed. Despite much debate, and the removal of one side of the crack (excluding the tip) for metallurgical analysis, no satisfactory explanation for the existence of this crack was obtained. The depth of the boiler chemical deposit on the crack face implied that the crack had existed for some time but, the absence of a reported leak during the boiler pressure test at the end of CSP00 implied that it had probably not existed through-wall prior to this point. The inability to remove the crack tip for analysis (due to its proximity to the next ligament hole (FIGs.3 & 4) and the need to leave some material for the weld repair to bond to) prevented confirmation of whether the crack was stable or active. A consensus of opinion, however, was that the crack was stable.

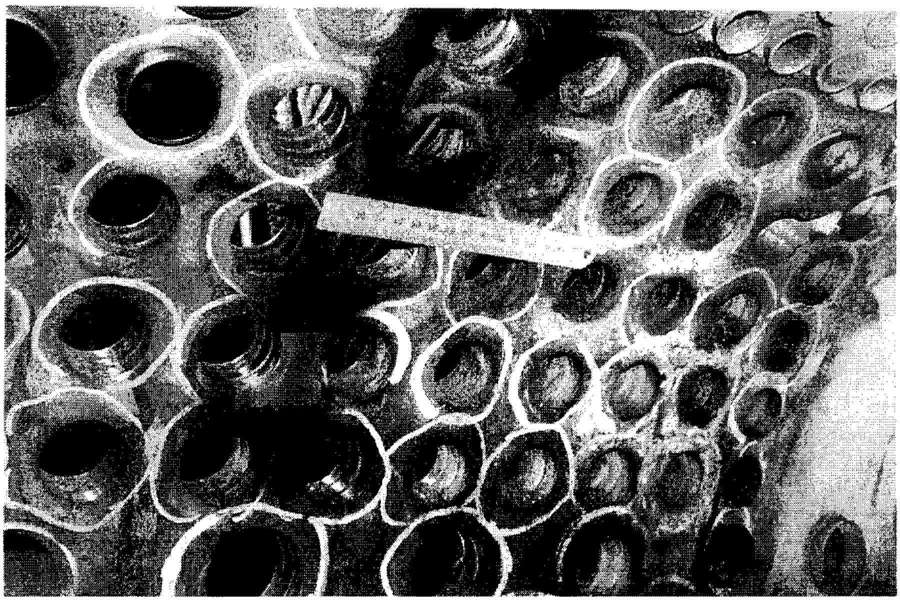


FIG.3 – VIEW INSIDE AMS WATER DRUM SHOWING HEAT AFFECTED 'HALF-MOON ZONES,' G14 CRACK CUT OUT (TOP RIGHT) AND 'BELLING ON TUBES'

Boiler repair

In parallel with the investigation into the mechanism behind the cracking, repair of the 5 identified cracks was conducted in accordance with standard practice.

Separate repair processes were considered and developed to remove all cracks and return the boiler to a condition suitable for further steaming. This lead to the adoption of the temper bead weld repair process (recommended by the Original Equipment Manufacturer) for the cracks at tube holes G14 (24mm) and C6 (8mm). For the 3 smaller cracks around water drum tube SR2, it was decided to bore out and fit an oversized tube, validated by stress calculations ensuring ligament integrity.

Although the weld repair process adopted was recognized and fully documented, the process was proved by trials on the boiler of the sister ship, *Intrepid*. All repairs were subjected to full analysis with the radiographs of the welds passed to an independent assessor, Royal and Sun Alliance, as an additional confidence measure. On completion, the boiler was subjected to a 1.5 x strength test.

Establishing Confidence

At this point, although processes were in place to restore the AMS boiler to a materially sound condition, confidence in both:

(*a*) The possibility that an as yet unidentified crack(s) may still be present and growing.

(*b*) That the DERA/Mitsui Babcock/Lloyds consortium may be wrong and that a crack might yet develop during subsequent operation was still not high.

These concerns were further compounded by the possibility that a very small crack may have been invisible to the available NDE techniques due to the 3mm (approx) 'belling' overhang of the tubes on the water side of the ligament plate (FIGs.3&4).

In addition, there was still a very real concern that the FMS boiler, which had been subjected to identical tube removal/replacement processes in CSP00 and CSP01, may also be harbouring undetected cracks.

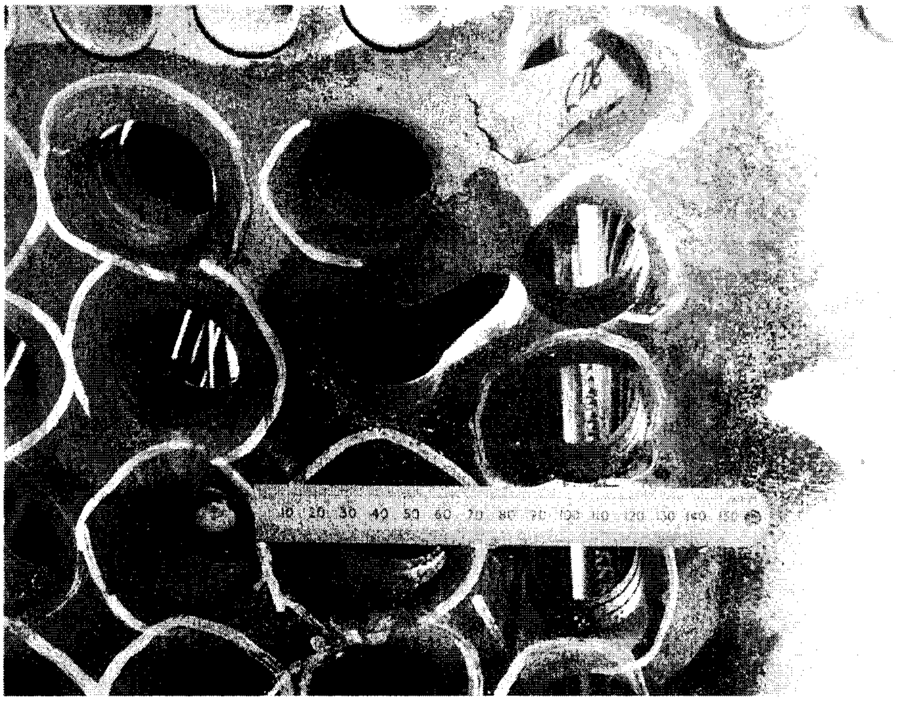


FIG.4 – VIEW INSIDE AMS WATER DRUM SHOWING CLOSE UP OF G14 CRACK CUT OUT

Further inspections were clearly necessary but this in itself posed various questions. Firstly, what NDE tool could be used – and what would be small enough to see under the belling? For the 35 years of the ship's life, full confidence had been placed in the MPI technique but this method was now in question. A search of other techniques quickly dismissed radiography – as inappropriate for a blanket search – and attention was homed on the eddy current method, although again, the blanket search requirement ruled out the proven, or most obvious tools. Attention was soon focused on a tool marketed and operated by NEWT International, a relatively new Portsmouth based company, which had gained acclaim during Railtrack's autumn 2000 cracked rail investigation programme. A particular advantage of this technique being that the manufacturer claimed that:

- A high surface finish prior to use was not necessary.
- The small diameter of the 'search' probe would allow it to be placed within the tube bores and thereby scan through the tube material into the ligament plate, avoiding the problem of the belling overhang.

However, attractive as the tool at first appeared, it was clear that much development would need to be conducted to modify the tool (from a 'plate search role') so that it was capable of accurate and consistent insertion into each tube so that comparable results could be obtained.

Secondly, the necessity to progress the rebuild and Set To Work (STW) that part of the AMS auxiliary machinery damaged in the fire so that the planned deployment date could be met, imposed severe constraints on the time available for further analysis. In light of this requirement, and given the lack of known defects in the FMS boiler, it was agreed that it was not unreasonable to allow a limited period of operation for plant proving, cross-connecting the FMS boiler to supply AMS equipments as necessary. This process was conducted satisfactorily over a 500 hour period in parallel with the repairs to the AMS boiler. On completion, the FMS boiler was shutdown and subjected to a full MPI survey. No cracks were found.

Defence in Depth

Taking the worst case, and assuming that cracks were still present in both boilers and possibly still growing, a series of defence in depth confidence measures were commenced. These included:

Finite Element and Fracture Analysis.

A 3D computer model of a 9 tube hole segment of the drum, modelling the internal pressure and tube rolling loading, was produced by Mitsui Babcock. This led to the production of stress profiles which, when compared to a range of empirical solutions selected from literature, was used to represent various boiler drum stress configurations in a fracture analysis. From this analysis, the critical defect size for a straight linear defect was calculated. The critical defect sizes, defined as when a crack had grown to a position where catastrophic drum failure was imminent, were calculated at between 192mm and 444mm respectively based on the toughness for the heat-affected (Martensitic) regions and the parent plate.

As it was known that operator notice could be assured for a crack approaching a size equivalent to the failure of a 1 inch boiler tube (a practice which is not uncommon and for which emergency operator actions are well rehearsed), it was concluded that the mechanism of failure in the parent plate would most likely be Leak-Before-Break (LBB). Therefore, if this were the case, it would be most unlikely that the boiler would fail in an unstable manner without prior warning under normal operating conditions.

Laboratory Work

In order to support the theoretical analysis, and also to remove the onus for some of the investigative work from *Fearless*, a laboratory based test programme using samples of water drum steel extracted from *Intrepid* was commenced. The Newcastle University metallurgical laboratories were selected for the work, and the objectives were to determine data on K1scc and crack growth rates in representative samples of boiler water for both the parent metal and for the Martensitic zones.

Without this knowledge, the only relevant data on crack growth rates originated from the G14 crack, where 24mm of growth had occurred in the 2,018 hours steaming between end CSP00 and the AMS fire (longest crack over shortest time). Based on a linear crack growth rate, and assuming that 2 cracks could grow concurrently from adjacent holes, across half a ligament each (12.5mm), then a ligament rupture could occur in approximately 1,000 hours. In theory, this implied that a concurrent initiation, and simultaneous propagation, of cracks from an aligned array of 7 adjacent tube holes could result in the critical defect length being achieved in 1,000 hours (6 x 25mm ligaments spans plus 7 x 50mm (2 inch) tube holes = 500mm). Clearly, reliance on this data would have severe limiting implications in any subsequent safety case.

Consequence Analysis

As a further layer of defence, an investigation was put in place to assess the ability of the boiler casing, with a wall thickness degraded by 50% (a realistic assumption given the age of the ship), to retain any fragments from brittle fracture of the boiler steam and water drums.

Through Life Management System

To further support the theoretical confidence in the boilers, it was decided to impose a rolling programme of full NDE inspections on the boilers. Taking the end of CSP01 as the datum point, these were planned as immediately prior to the deployment, which equated to approximately 1,000 hours for the FMS boiler, and again at the end of the deployment, which would equate to approximately 5,000 hours for the FMS boiler. For the AMS boiler, which lagged its counterpart by 500 hours, the option to insist on an inspection at the 1,000 hour point, equating to a point in mid-deployment (Marmaris, Turkey) was retained. In addition, a 500 hour extension to all dates was agreed should the ship be required to conduct essential humanitarian aid operations.

Initial Safety Case

Authority for *Fearless* to sail for essential pre-deployment training (work-up) was granted in early July. At this stage, there being a 500 hour mismatch between the boilers, the licence allowed the FMS boiler to operate to a total of 1,000 hours, and the AMS boiler to 500 hours (from end of CSP01).

As both boilers were going into service with residual Martensitic regions around the tube holes, but with all detectable cracks removed, the potential for further cracking could not be dismissed. The safety case for continued steaming would, therefore, have to be based on the limited known information, namely the time taken for the worst crack (G14 – to grow to 24mm) over the shortest time span (2,018 hours). In the absence of other data, a linear crack growth rate had to be assumed. Given that 'the 2 simultaneous cracks growing over a 25mm ligament space' argument would still allow a factor of safety in a 500 hour operating period, it was considered reasonable to endorse the required 500 hours operation, supported by this information plus the knowledge that no new cracks had appeared in the FMS boiler in the previous 500 hour plant proving period.

Further Investigations

On return to Portsmouth following completion of the 500 hour work-up period, full MPI NDE was conducted of all 4 boiler drums. No defects were found and the FMS boiler was closed up. At this point, the options available were widened by the arrival of the NEWT eddy current technique and the decision was taken to deploy the tool on the still open AMS boiler.

NEWT quickly found 21 cracks (all between 5-8mm long except steam drum E3, which was found to be 10 mm long), of which 5 existed in Row D of the steam drum. These locations were rechecked with MPI but, in all but 2 cases (tube A1 (5mm long) and tube D12 (1mm long)), no correlating indications could be found. In addition, the defect at D12 was assessed as a 'surface imperfection' – possibly a scribe mark originating from boiler manufacture. As NEWT's technique was still considered to be largely experimental, and that the operators were unused to Marine Boilers, the possibility that they had mistakenly recorded identified defect sites could not be ruled out.

Follow on Safety Case

Fearless was due to deploy for the autumn training exercise in mid August and, accordingly, all interested parties reconvened to consider on what basis further safe operation could be supported. Recapping, this consisted of:

(*a*) All 'confirmed cracks' in the AMS boiler had been repaired.

(*b*) No cracks had been found in the FMS boiler, either initially or at the recent 1,000 hour MPI inspection.

(*c*) An MPI inspection of the AMS boiler at the recent 500 hour point had initially given a clear bill of health but, when challenged by the NEWT technique, had subsequently confirmed the 2 small 'cracks or defects' at steam drum tubes A1 and E3.

(*d*) NEWT had found 21 'cracks' in total (15 in the steam drum, 6 in the water drum) although the somewhat prototypical nature of the tool needed to be taken into account.

(*e*) The FE analysis had identified the critical crack length plus the fact that any failure was likely to be LBB.

(*f*) The metallurgical samples at Newcastle University, despite being stressed to greater levels than likely within the boiler (and also having been conducted in more adverse chemistry conditions) had failed to show any crack growth after a few hundred hours. Therefore, although extremely pessimistic, the only available crack growth rate data remained that from the G14 crack.

(*g*) The probability and consequence of brittle failure of the drum had been addressed. This had included studies of the ability of the boiler casing to retain any fragments, the likely risk to personnel, the ship or down stream secondary damage caused to other equipment (e.g. ejected missile fracturing a fuel pipe). Although not taken further at this point, consideration of the mitigation, which might be gained by amendments to standard operating practices, had also been considered.

On a more subjective analysis, it was considered that all the evidence available presented a picture of the boiler in its worst case. In particular, the G14 crack growth rate used in the analysis was considered to be extremely pessimistic, and many potential arguments could be established allowing the use of a slower crack growth rate. Likewise, the NEWT results, if accepted as a true representation of the AMS boiler, instead of the MPI results, also presented a gloomy picture. No hard evidence was available to lessen this worst case data but, on the other hand, no argument could be put forward to warrant the basing of the analysis on even greater pessimism either. After due consideration, it was considered that there was no overriding reason why the ship should not be deployed so long as the option to inspect the AMS boiler at the 1,000 hour point was exercised. Accordingly, the AMS boiler was licensed to 1000 hours, and the FMS boiler was licensed to 5,000 hours, subject to:

> "No new defects being found in the AMS boiler at the Marmaris inspection and no other challenge being presented to the current understanding of the defect mechanism."

Preparation for Inspection at Marmaris, Turkey

By the time of the planned inspection, it was realised that the samples from *Intrepid* on test in Newcastle would have reached the 1,000 hour point. Assuming that no cracks would have developed by then, and given that no further challenge to the understanding of the cracking mechanism had been forthcoming from the theoretical work, it was considered that a satisfactory inspection result in Turkey would provide enough evidence to restore a full boiler operating licence. In turn, this implied that resolution of the difference between the various NDE techniques was paramount and a programme of work to improve available resources was commenced. This involved:

(*a*) Conducting trials of MPI under UV lighting, rather than white (this had been tried before but abandoned due to poor surface preparation). Accordingly preparations to clean the internal surfaces of the drums to a high standard were put in hand.

(*b*) Incorporation of significant improvements to the prototype NEWT probe and conducting a trial of the revised equipment in the boiler of HMS *Intrepid*.

(*c*) Inclusion of the established polish, etch and replication techniques in the NDE programme; etching to determine the Martensite/parent metal boundary and replication (metal foil and microscopic examination) to allow unequivocal analysis of any identified defects.

In addition, should any cracks be confirmed, a local burring technique was developed to allow removal of cracks down to 9mm in depth. It was considered that this technique, if applied to some, or all, of the cracks in steam drum Row D, would significantly remove the possibility of a 'zipper type' defect. A priority list for the removal of NEWT–identified cracks was also drawn up, as were instructions for the possible retention of a confirmed crack to allow monitoring of the crack growth rate to take place over the period to the next planned inspection in December 2001, the 5,000 hour point.

Other preparations included the preparation of a comprehensive boiler tube mapping system so that the possibility of inaccurate defect recording or possible confusion between the crack length and the Martensite boundary interface could be minimized. This was considered particularly beneficial given the relative lack of marine boiler experience possessed by NEWT International.

Inspection at Marmaris

In the event, the inspection of the AMS boiler at Marmaris proceeded smoothly, at a brisk pace and with no confusion over crack identification. Great attention was paid to surface preparation and the inspection started from a very clean and condensation free datum. Although the improved NEWT technique picked up several crack indications in the steam drum, all but one – A1 – disappeared when subjected to a light dressing/polishing. As expected, the MPI technique, deployed on very clean metal under UV lighting, only picked up the A1 defect which, at 5mm long, could also be seen with the naked eye. No defects were found in the AMS water drum.

All previously identified NEWT cracks were subjected to a comprehensive etch and replication survey at the reported (o'clock indication) and also at the cardinal points for additional confidence (in case the original report had been incorrect), and all were found to be clear of cracks. The greatest extent of Martensite at these sites was found to be 10mm from the tube bore, and the defect at AMS steam drum hole A1 was proved, by replication, to be a metal fold, dating from original manufacture. This latter point was confirmed by the stable metalographic structure around the 'crack' replication, and the discovery of a tiny fleck of red paint near the tip. This 'defect' was assessed as presenting no threat to the integrity of the boiler.

For completion, the weld repair sites were also checked, and the surround to the bore-out repair at tube SR2 was etched to ensure that all Martensite had been removed. No defects or evidence of further Martensite were found.

There being no evidence of any cracks in the AMS boiler by MPI, NEWT's eddy current technique or replication, coupled to the previous clear results obtained from the FMS boiler prior to deploying. Full confidence in the MPI technique was restored and *Fearless*'s ATO was re-instated, allowing her to continue with her deployment. At the time of writing, a decision on whether the 5,000 hour inspection, as required by the Through Life Management System, would still be required has not yet been made.

Conclusions

The following conclusions can be drawn from this experience:

- (*a*) HMS *Fearless*'s AMS boiler was damaged by contractors removing tubes with oxy-acetylene cutting equipment, contrary to standard, long established practice. The mechanism of cracking was somewhat unusual in that a Martensite precursor was able to form as a result of localized (oxy-acelylene) heating and bulk cold metal quenching. Although an identical process was used in the FMS boiler, no cracks were found.
- (*b*) Hardness testing may be used to confirm the presence of Matensite.
- (*c*) The MPI technique can be relied upon to find defects, but only if applied with due operator diligence. MPI under UV light gives a greater degree of confidence, but will require a far higher standard of surface preparation.
- (*d*) The NEWT eddy current NDE technique is extremely sensitive to minor surface imperfections or loose surface scale, but can be relied upon to find surface breaking defects.
- (*e*) Restoration of confidence is a long and time consuming process.

Lessons learnt

Clearly several lessons were learnt from this entire process. Perhaps the most significant of these were:

- The transfer of maintenance authority from the Crown to a Contractor will, unless closely monitored, result in significant changes to established maintenance routines as exploitation of cost savings are made. Every effort should be made to monitor any such changes to ensure that design intent is not jeopardised.
- Localized use of intense heat in a bulk-metal environment may lead to the formation of Martensite with a consequent effect on the material's design properties.
- Periodic NDE inspections, particularly long established routines, have an Achilles heal:

  > If operators don't expect to find defects – they won't.

  In particular:

  > Operators must expect to find cracks and must not be lulled into a false sense of security merely because of the longevity of the technique and the previous history of 'blank inspections.'

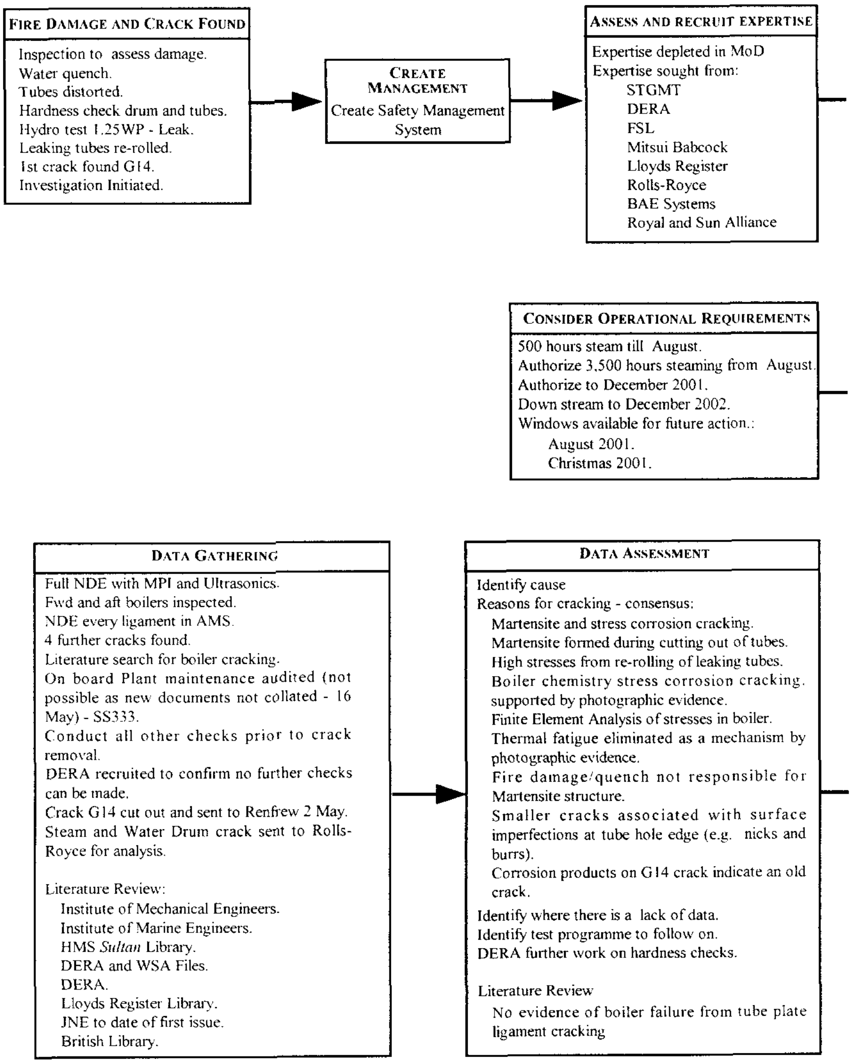
- When system confidence is challenged or lost, neither the enormity of the process, in terms of time and cost, needed to restore it, nor the extent of the search for qualified, independent technical experts should be underestimated.
- The results from new analytical equipment or processes, particularly if rushed into service to meet operational deadlines, should be carefully considered against all other sources of information before action, based solely on their results, is taken.

Closeout

Obsolescence management is now a well recognized science and few major projects fail to acknowledge the need at early stages of the development cycle. What is not so readily acknowledged is the requirement to maintain a current, and credible, experienced resource bank through the twilight stages of an equipment's life. It is hoped that the description of the *Fearless* investigation in this article will help illuminate this need.

ANNEX A

HMS 'FEARLESS' BOILER LICENSING MANAGEMENT PROCESS



Fire Damage and Crack Found

Inspection to assess damage.
Water quench.
Tubes distorted.
Hardness check drum and tubes.
Hydro test 1.25WP - Leak.
Leaking tubes re-rolled.
1st crack found G14.
Investigation Initiated.

Create Management

Create Safety Management System

Assess and recruit expertise

Expertise depleted in MoD
Expertise sought from:
- STGMT
- DERA
- FSL
- Mitsui Babcock
- Lloyds Register
- Rolls-Royce
- BAE Systems
- Royal and Sun Alliance

Consider Operational Requirements

500 hours steam till August.
Authorize 3,500 hours steaming from August.
Authorize to December 2001.
Down stream to December 2002.
Windows available for future action.:
- August 2001.
- Christmas 2001.

Data Gathering

Full NDE with MPI and Ultrasonics.
Fwd and aft boilers inspected.
NDE every ligament in AMS.
4 further cracks found.
Literature search for boiler cracking.
On board Plant maintenance audited (not possible as new documents not collated - 16 May) - SS333.
Conduct all other checks prior to crack removal.
DERA recruited to confirm no further checks can be made.
Crack G14 cut out and sent to Renfrew 2 May.
Steam and Water Drum crack sent to Rolls-Royce for analysis.

Literature Review:
- Institute of Mechanical Engineers.
- Institute of Marine Engineers.
- HMS *Sultan* Library.
- DERA and WSA Files.
- DERA.
- Lloyds Register Library.
- JNE to date of first issue.
- British Library.

Data Assessment

Identify cause
Reasons for cracking - consensus:
- Martensite and stress corrosion cracking.
- Martensite formed during cutting out of tubes.
- High stresses from re-rolling of leaking tubes.
- Boiler chemistry stress corrosion cracking. supported by photographic evidence.
- Finite Element Analysis of stresses in boiler.
- Thermal fatigue eliminated as a mechanism by photographic evidence.
- Fire damage/quench not responsible for Martensite structure.
- Smaller cracks associated with surface imperfections at tube hole edge (e.g. nicks and burrs).
- Corrosion products on G14 crack indicate an old crack.

Identify where there is a lack of data.
Identify test programme to follow on.
DERA further work on hardness checks.

Literature Review
- No evidence of boiler failure from tube plate ligament cracking

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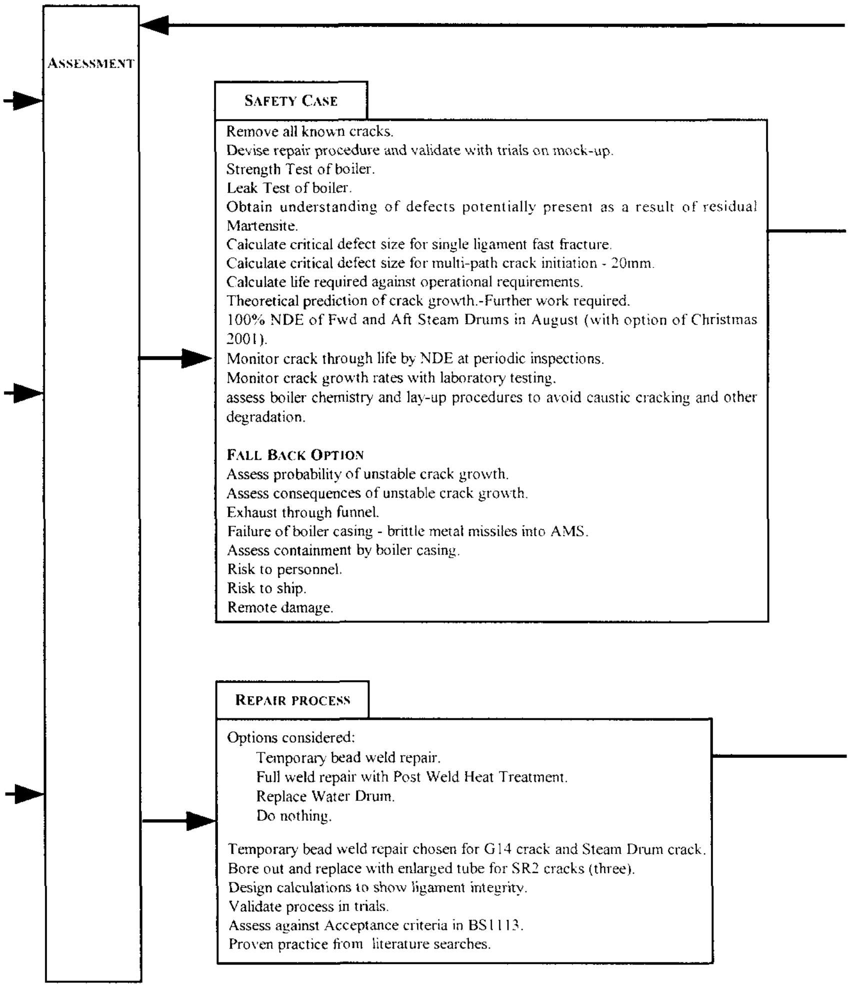

SAFETY CASE

Remove all known cracks.
Devise repair procedure and validate with trials on mock-up.
Strength Test of boiler.
Leak Test of boiler.
Obtain understanding of defects potentially present as a result of residual Martensite.
Calculate critical defect size for single ligament fast fracture.
Calculate critical defect size for multi-path crack initiation - 20mm.
Calculate life required against operational requirements.
Theoretical prediction of crack growth.-Further work required.
100% NDE of Fwd and Aft Steam Drums in August (with option of Christmas 2001).
Monitor crack through life by NDE at periodic inspections.
Monitor crack growth rates with laboratory testing.
assess boiler chemistry and lay-up procedures to avoid caustic cracking and other degradation.

FALL BACK OPTION

Assess probability of unstable crack growth.
Assess consequences of unstable crack growth.
Exhaust through funnel.
Failure of boiler casing - brittle metal missiles into AMS.
Assess containment by boiler casing.
Risk to personnel.
Risk to ship.
Remote damage.

REPAIR PROCESS

Options considered:
- Temporary bead weld repair.
- Full weld repair with Post Weld Heat Treatment.
- Replace Water Drum.
- Do nothing.

Temporary bead weld repair chosen for G14 crack and Steam Drum crack.
Bore out and replace with enlarged tube for SR2 cracks (three).
Design calculations to show ligament integrity.
Validate process in trials.
Assess against Acceptance criteria in BS1113.
Proven practice from literature searches.

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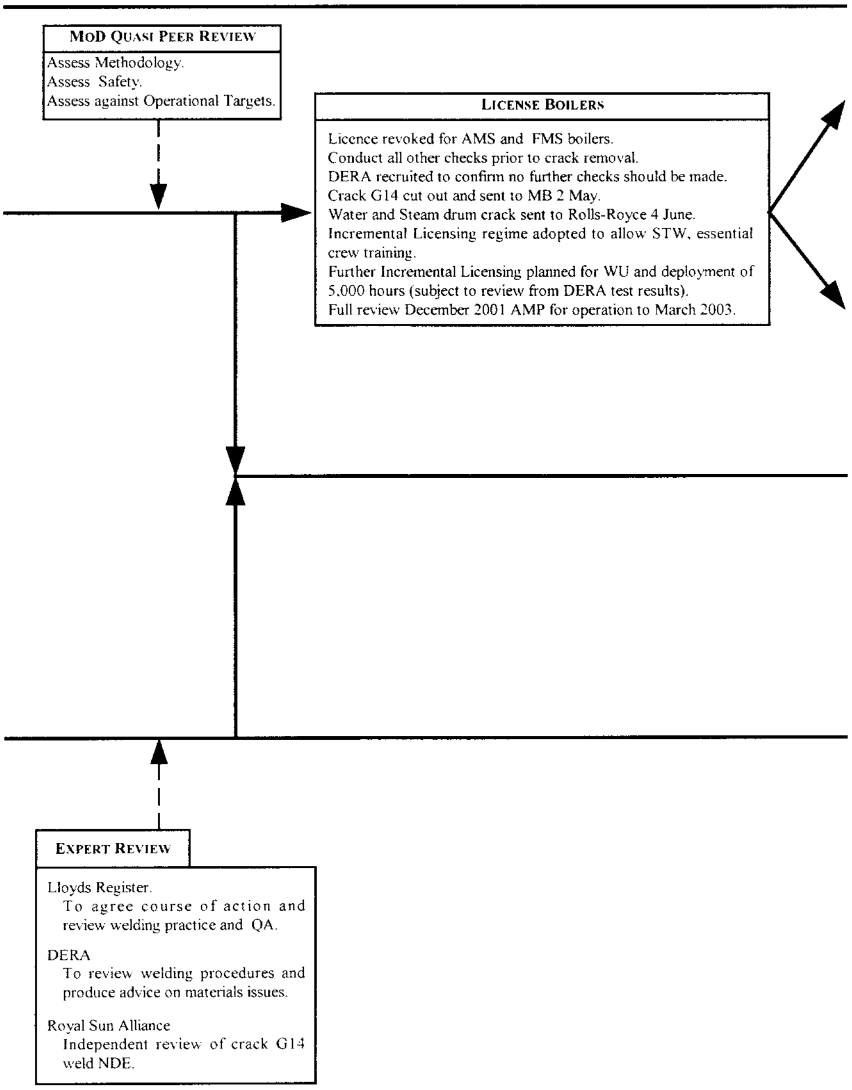

MoD QUASI PEER REVIEW

Assess Methodology.
Assess Safety.
Assess against Operational Targets.

LICENSE BOILERS

Licence revoked for AMS and FMS boilers.
Conduct all other checks prior to crack removal.
DERA recruited to confirm no further checks should be made.
Crack G14 cut out and sent to MB 2 May.
Water and Steam drum crack sent to Rolls-Royce 4 June.
Incremental Licensing regime adopted to allow STW, essential crew training.
Further Incremental Licensing planned for WU and deployment of 5,000 hours (subject to review from DERA test results).
Full review December 2001 AMP for operation to March 2003.

EXPERT REVIEW

Lloyds Register.
To agree course of action and review welding practice and QA.

DERA
To review welding procedures and produce advice on materials issues.

Royal Sun Alliance
Independent review of crack G14 weld NDE.

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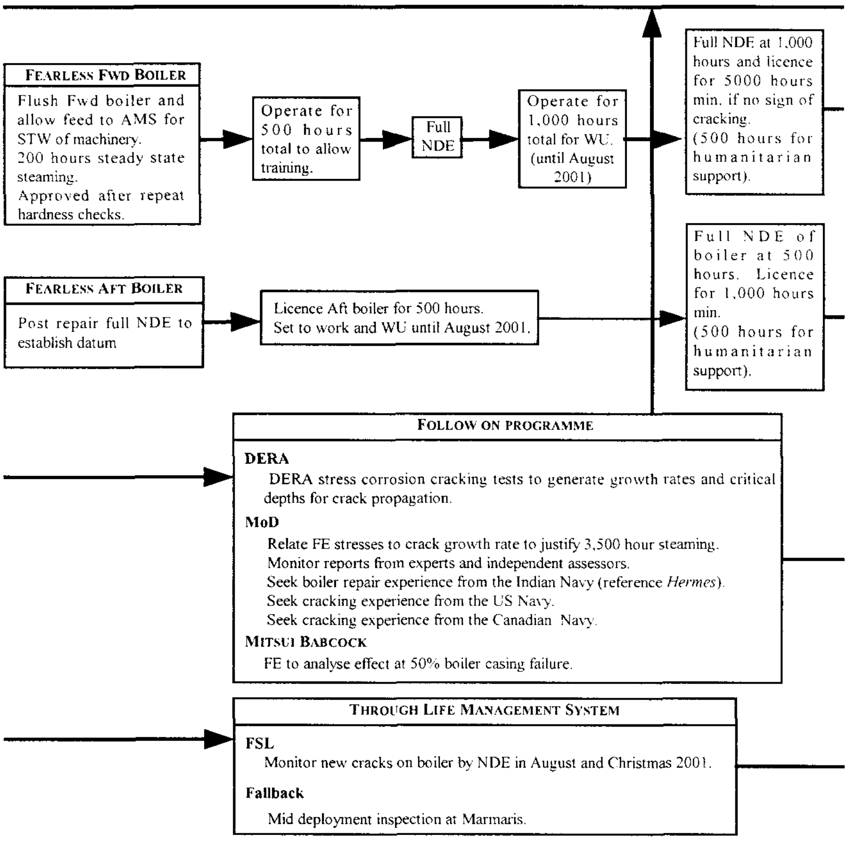

FEARLESS FWD BOILER

Flush Fwd boiler and allow feed to AMS for STW of machinery.
200 hours steady state steaming.
Approved after repeat hardness checks.

Operate for 500 hours total to allow training.

Full NDE

Operate for 1,000 hours total for WU. (until August 2001)

Full NDE at 1,000 hours and licence for 5000 hours min. if no sign of cracking.
(500 hours for humanitarian support).

FEARLESS AFT BOILER

Post repair full NDE to establish datum

Licence Aft boiler for 500 hours.
Set to work and WU until August 2001.

Full NDE of boiler at 500 hours. Licence for 1,000 hours min.
(500 hours for humanitarian support).

FOLLOW ON PROGRAMME

DERA
DERA stress corrosion cracking tests to generate growth rates and critical depths for crack propagation.

MoD
Relate FE stresses to crack growth rate to justify 3,500 hour steaming.
Monitor reports from experts and independent assessors.
Seek boiler repair experience from the Indian Navy (reference *Hermes*).
Seek cracking experience from the US Navy.
Seek cracking experience from the Canadian Navy.

MITSUI BABCOCK
FE to analyse effect at 50% boiler casing failure.

THROUGH LIFE MANAGEMENT SYSTEM

FSL
Monitor new cracks on boiler by NDE in August and Christmas 2001.

Fallback
Mid deployment inspection at Marmaris.

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