SECTION 2 - ANALYSIS

The purpose of the analysis is to determine the circumstances and contributory causes of the accident, as a basis for making recommendations to prevent similar accidents in the future.

2.1 RUPTURE OF THE ECONOMISER

Two men lost their lives when extremely hot water and steam drenched them following the rupture of *Island Princess*'s port economiser.

The investigation found clear evidence, from plastic collapse of the shell-plating ahead of a fatigue crack, that the catastrophic rupture was due to overstressing. This was caused by pressure building up inside the economiser when steam could not escape through the safety valves. Although those responsible for opening them thought they had done so by operating the easing gear, the safety valves had, in the event, remained shut.

The investigation noted that the shell-plates of *Island Princess*'s starboard economiser, and the *Pacific Princess* and *Sun Princess* economisers, had suffered barrelling similar to that of the ruptured economiser. For this to happen, the economiser safety valves must have seized sufficiently to develop a pressure build-up and consequent overpressure.

It is not possible to establish if the ruptured economiser had been overpressurised before the accident. It was surveyed in 1997, when no barrelling effect was reported. However, it is difficult to detect such deformation unless the shell-plate lagging is removed. The lagging was not removed when the economiser was surveyed.

The actual pressure reached at the time of rupture is uncertain, but it has been estimated to be over four times working pressure, and was caused by seizure of the safety valve.

The safety valve tests in Naples were performed in cold conditions, and the jacking tests were undertaken three months after the accident. Both these factors would affect the degree of seizure. Even so, because they failed to release at a minimum equivalent steam pressure of nine times working pressure, it is reasonable to assume that at the time of the accident they were seized sufficiently to cause overpresssure. The pressure in the economiser, combined with the weakening effect of the corrosion fatigue cracks on the shell-plate, resulted in its rupture.

2.2 FATIGUE CRACKS

As stated in sections 1.8 and 1.9, it is known that the internal fillet weld of shell-to-endplate in economisers and oil-fired boilers is sensitive to fatigue cracking at the weld toe.

In 1994 cracks appeared in the economiser of *Pacific Princess*. In 1995 similar cracking occurred in *Island Princess*. Given the findings of the examination of *Island Princess*'s ruptured economiser, these cracks were probably caused by corrosion fatigue. They were deep and penetrated the full shell thickness. Princess Cruises wanted them to be repaired by gouging out the cracks and re-welding. LRS, and the MCA surveyors approved the repair, and accepted them on completion.

Fatigue cracking in shell type marine boilers

During service, marine boilers are subjected to fluctuating stresses caused by:

- application of pressure;
- temperature gradients;
- pulse vibration from main engines;
- restrictions of expansion or contraction during normal temperature variations.

It is the accumulated effect of these fluctuating stresses over a period of time that led to fatigue cracking.

Surface condition plays a dominant role in fatigue crack initiation, and is associated with changes in section and surface blemishes, such as rough welded surfaces. These features produce highly localised stress concentrations; preferred sites for fatigue crack initiation.

The rougher the surface, the higher the probability that a fatigue crack will initiate. A corrosive environment will significantly enhance this probability.

Fatigue crack initiation, found in the ruptured economiser, was localised in corrosion grooving at the shell-plate weld toe. The rate of crack propagation was subsequently enhanced by the presence of a local corrosive environment. Secondary incipient corrosion fatigue damage was also apparent adjacent to the ruptured surface.

SAFed Guidelines

The SAFed guidelines advise that shallow cracking and grooving, less than ¼ depth thickness at the toe of the fillet weld, may be repaired by gouging out and welding.

For deep-seated cracks, the guidelines do not recommend gouging out and welding from outside because of difficulties in:

- ensuring complete removal of the defect; and
- obtaining an adequate root profile.

They also advise that metallurgical and residual stress effects could lead to early recurrence of cracking in these areas.

These repairs can be difficult and ineffective on flat-ended shell-type boilers, because access to the waterside cracks may require removal of exhaust gas tubes, a time consuming and costly exercise.

Because of lack of access, it is difficult to obtain an adequate weld root profile when repairing deep-seated cracks from the outside of the shell-plate. An inadequate root profile leads to unacceptable stress concentrations, increasing the likelihood of fatigue crack growth.

This likelihood is increased further, since gouging out and welding of the crack will not remove localised incipient and secondary cracks in the area of corrosion grooving. These cracks, subjected to an aggressive environment, will result in further corrosion fatigue crack propagation.

Repair of corrosion fatigue cracks

The ineffectiveness of gouging out and welding a deep-seated crack was illustrated in the repairs to *Pacific Princess* and *Island Princess* economisers in 1994 and 1995 respectively. Post-accident inspection on both vessels found cracks in the repair weld. The *Island Princess* repair was found to be cracked at the waterside to 25% shell-plate thickness, (1.7.1), which occurred within three years of the repair. When these economisers were repaired, NDT examination was restricted to the newly welded areas.

The first evidence found of cracking on the *Pacific Princess* economiser in 1994 might have been seen as an isolated incident. If so, then gouging out and welding would have been a reasonable option, and a wider examination of the circumferential would have seemed unnecessary. When a similar pattern of cracking appeared on the *Island Princess* economiser less than two years later, the similarity should have been noted, and greater care taken to investigate the cause and to determine its extent.

The problem of cracking in these economisers should have been assessed by NDT examination of the whole length of the affected circumferential joints. The other circumferential joints should have been examined for cracking, and the reason for it identified. The Test House investigation concluded that these cracks might have been the result of a similar failure mechanism of corrosion fatigue as that identified in the failure analysis. If so, gouging out and welding of the deep-seated cracks was not an option.

The most effective way to remove corrosion fatigue cracks is to cut out a window, insert new metal and weld. Descaling the weld area before inserting the patch would give a better chance for an effective repair.

The patch could be inserted in two halves. The bottom could be welded on both vertical sides and on the bottom side in the critical location. Access through the now top opening would enable back welding. The top half patch would be fitted with one weld only (no back weld), and remote from the critical area.

Another option would be to insert a single patch, welded exclusively from both sides. To enable access to back weld, boiler tubes would have to be removed.

Promulgation of information on fatigue cracking problems

When its surveyors raise specific safety issues or concerns, LRS brings these to the attention of owners of affected vessels. It also promulgates general matters of safety to the marine industry through Lloyd's Register Marine Service Bulletins. LRS treated previous incidents of rupture and cracking of the Princess Cruise ships' economisers in isolation. They considered it unnecessary to inform the industry of the possibility of a more widespread problem. These were incidents which had possible fatal consequences. The accident on *Island Princess* was fatal, to indicate that, such incidents should not be treated in isolation in future.

Soon after the accident, LRS issued a service bulletin to surveyors, and a letter to shipowners. These advised to check the economiser circumferential seams at surveys for cracks, using ultrasonic or dye penetrant testing. The tests had to be made at survey or at the earliest possible time.

The MCA was responsible for issuing the Passenger Safety Certificate, which in part, was dependent on satisfactory survey and operation of the economisers. In this respect they were satisfied with the survey and repair requirements of the classification society, but like LRS, the MCA treated each incident in isolation. In so doing, it inadvertently fostered a perception that the economisers were low risk items.

The MCA, LRS, inspection organisations representing insurance interests in boiler installations ashore, and the HSE, have been aware of the problem of fatigue cracking at the weld toe in shell-type boilers since the 1970s. This awareness led to the publication of guidance notes on survey inspection and repair of shell-type fired and unfired boilers.

It is interesting to reflect that had such failure occurred on a land-based installation in the United Kingdom, insurance companies would probably have demanded an NDT survey of the entire length of the circumferential weld joints. Such companies have a direct vested interest in realising their insurance risk: a boiler failure costs them money. They therefore tend to work as a co-ordinated group to pool their collective experience and produce common documents on technical safety issues, such as the AOTC and SAFed published guidance notes.

The classification societies have a system for promulgating safety information collectively through the forum of International Association of Classification Societies (IACS). IACS regularly publish programmes which enhance ship safety. Unfortunately, neither they, nor the individual classification societies, nor the MCA, have published boiler information as detailed as that found in the AOTC and SAFed guidance notes. The MCA and IACS should consider doing so.

The ISM Code has only recently become mandatory on United Kingdom passenger ships. The code requires a safety management system which includes procedures to ensure that deficiencies, such as cracks in economiser circumferential seams, are reported, investigated and analysed. To what extent this investigation and analysis should take place is dependent on the understanding of the safety and pollution risk. The assessment of that risk in turn, is dependent on the professional knowledge and expertise involved. If surveyors, superintendents, ship's engineers and inspection organisations choose to ignore, or are unaware of, the lessons of history, then a realistic risk assessment will not be achieved.

Shipping companies, classification societies and flag states have a shared responsibility in ensuring that knowledge of incidents, and lessons learned from them, are distributed throughout the marine industry. It is in the best interests of safety to do so.

2.3 EXAMINATION OF BOILER FEED WATER

On *Island Princess* the feed water was common to the economisers and boilers. Similar constituents of precipitation from the boiler water were therefore expected to be found in both. However, that found in the economisers consisted of hard scale, while that in the oil boiler was soft sludge. Sludge is a by-product of proper boiler water treatment. Hard scale is the result of untreated hardness constituents of the boiler water settling out on to hot surfaces.

As widespread practice, Princess Cruises used consultants to advise on chemical treatment of the boiler water. The engineers monitored and controlled the treatment in accordance with advice given. However, The Test House analysis of the sludge and hard scale samples, indicated that the chemical water treatment was not always able to cope with the contamination.

Since *Island Princess*'s replacement oil-fired boilers were fitted in 1989, there have been problems with excessive build-up of sludge that has resulted in overheating and structural failure despite regular blowing-down and regular cleaning of the boilers' waterside. Princess Cruises considered that the boiler blowdown arrangements were ineffective in clearing sludge from the boilers. Following the accident however, the oil-fired boiler blowdown arrangement was modified to improve its efficiency.

The analysis of scale and sludge samples, and examination of the water-treatment records, shows that feed water contamination was intermittent. The source of contamination has not been firmly established, but could have been from excessive carry-over from evaporators, leaking heat exchangers and/or brackish shore water.

Princess Cruises blamed contaminated shore water taken on board for the sludge build-up in the boiler water controller of the starboard boiler. The procedures for flushing out the oil-fired boilers is documented in the "Works Procedures Index Report" as part of the safety management system. These procedures were not totally effective.

Notwithstanding the problems with poor shore water quality in Naples, the evidence suggests that the water quality was a long-standing issue.

Some of the hard scale deposits found in the economisers may have been present since the boiler change in 1989. Any sludge that might have been in the port economiser before the accident would have been lost when it discharged its water on rupture.

Maintaining the waterside of economisers and boilers in a clean condition reduces the possibility of fatigue corrosion, and assists in locating defects, such as fatigue cracks, during inspection. However, unlike the oil-fired boilers, the economiser watersides were not regularly cleaned and descaled. A procedure for such cleaning was not included in the safety management system.

2.4 CAUSE OF SEIZURE OF *ISLAND PRINCESS*'S SAFETY VALVES

Safety valves provide the last line of defence against the possibility of boiler overpressure and explosion. It is essential, therefore, that they are subject to regular and routine inspections and tests by the classification society and the ship's engineers.

2.4.1 Seizure of safety valve spindle in guide bush

This type of valve was a standard fitting to Aalborg economisers. In 1975, Princess Cruises, LRS and the MCA accepted the fitness of these valves for use on these economisers. There was no reason then for them not to do so.

In 1979 after rupture of the *Pacific Princess* economiser, the possibility of safety valve seizure was realised, so there was an added need for greater care and attention when operating and maintaining them. This need was not satisfied: safety valves have since seized, economisers have overpressurised and an economiser on *Island Princess* has ruptured.

The spindles of *Island Princess*'s port economiser safety valves seized in their guides because of spindle corrosion damage, accumulation of corrosion products, boiler sludge deposits and other extraneous material at the spindle to guide bush interface.

NordAmatur's stainless steel specification for the valves spindle was found to be very similar to that used by at least three leading United Kingdom manufacturers of safety valves, which is 420 and 429 type stainless steel. It is reasonable to conclude therefore that NordAmatur's specification was an acceptable industrial norm.

The Test House found that the port economiser safety valves would not be expected to suffer from corrosion in clean steam conditions. This concurred with NordAmatur's literature which advised that they were suitable for steam, water, and gases which do not attack the materials of the valves. However, it was found that the spindle material selection could be susceptible to corrosion at elevated temperature with steam/water discharges containing high levels of TDS. Feed and boiler water condition was a recurring problem in the steam plant. Thus, since the economiser operated in a flooded condition, the water/steam discharge across the valve resulted in hardness salts condensing on the valve stem/guide surfaces. Leakage of the safety valves seems to have been a recurring problem; this having a significant effect on the corrosion rate of the spindle and its susceptibility to seizure.

The corrosion rate is impossible to quantify. However, although the aft safety valve spindle and guide were freed and cleaned in August 1997, seizure recurred less than three months later. No attempt had been made to restore the leaking valve surfaces to make them steam/watertight, consequently the valve continued to leak. The seized forward valve had also leaked.

The NordAmatur instruction manuals advised that the seat in the valve body and the valve lid should be lapped separately using lapping mandrills.

A senior engineer confirmed that it was usual for the two seating surfaces to be lapped in together without using mandrills. This was a procedure which the instructions specifically warned against.

It seems that the required lapping tools were not used on board *Island Princess*. On his visit to the NordAmatur factory and its safety valve service section, the inspector observed that the safety valve service technician attached great importance to complying with recommended lapping procedures. Lapping the two surfaces together to obtain an effective seal was considered as an impractical and fruitless task.

Safety valve spare parts and servicing

Renewal of damaged safety valve spindles and guides was crucial to reducing risk of seizure. A detailed spare parts list such as that listed in NordAmatur's instruction manual and order references displayed on the valve body identification plate would have facilitated a correct order for spare parts. But this manual and the spare parts list were not on board, and the identification plate was covered in paint and impossible to read. Indeed, it took The Test House two days to remove the paint using a range of solvents and paint stripper.

There is no evidence to show that spare guide bush and spindles were on board at the time of the accident. It is unlikely, since Princess Cruises have no record of any safety valve spare parts being ordered or used.

Suitable spare parts were on the shelves at the NordAmatur works in Linköping, ready to dispatch to customers at very short notice. NordAmatur also had a network of distribution agents worldwide. With such a system, there was no excuse for not fitting manufacturer's specified components.

If there were no resources immediately available for overhauling safety valves, NordAmatur had the facilities for carrying out the work. These facilities are accredited by Swedish regulatory bodies and classification societies.

The engineers on board *Island Princess* seemed to have been unaware that a non-ferrous sintered bronze glacier guide bush was fitted to the valves. One senior engineer had assumed that plain bronze guides were fitted, a type of guide fitted to safety valves in general. The engineer who dismantled the valve in August 1997 to free the aft valve spindle, considered that there was no need to replace any components. He too, was probably unaware of the nature of the sintered bronze guide.

The Test House found the thin non-ferrous internal lining of the spindle guide bushes was damaged with total loss of lining thickness in some areas. The damage was probably mechanical, resulting from earlier seizure and cleaning with abrasive materials such as emery cloth. Given the level of metal loss, it is reasonable to assume that thinning of the lining existed in August 1997. Had the engineers known of the guide and recognised the damage, they would not have been confident in its continued use.

Unlike a solid bronze bush, the sintered bronze lining has a delicate surface less than 0.20mm thick, which is easily penetrated. Some of the hammer marks found on both spindles predated the accident, and were signs that they had been seized and freed by hammering them out. This action alone could result in damage to the lining surface, making replacement of the guide necessary.

The clearance between valve stem and bush must be sufficient to allow movement under all conditions of service and is based on the competent judgement of the manufacturer. The choice is an important factor to avoid corrosion and the effects of corrosion deposits interfering with freedom of movement in the stem guide.

In the case of the NAF safety valve, the manufacturers' choice of clearance is based on the specification requirements for the Glacier bush. Glacier specify a tolerance clearance and a value of surface smoothness on the valve spindle.

It is reasonable to expect that spare parts specified by the manufacturer are fitted to the valve. Otherwise the chance of improper operation and repair is increased.

Knowledge of the principles involved with characteristics, operation, testing and maintenance of boilers and their mountings is a requirement of the Class 1 and 2 Certificate of Competency for marine engineers. In this respect, they should understand the principle of the relatively simple operation of the NAF 5463438 safety valve. However, their knowledge of particular makes of valves, or the design of individual components, is not tested. In the case of the NordAmatur valve, for example, without the guidance outlining the presence of the sintered guide bush they would not be expected to know about it. Neither instruction manuals described in section 1.12 gave construction and material detail of components.

Usually guide bushes are simply constructed plain bearings made of solid non-ferrous material, which does have the complexity of the thin composite bearing surface featured in the NordAmatur bush.

It is therefore understandable that engineers with only a general knowledge of safety valves were unaware of the special features of the NordAmatur bush, and the need for its replacement.

On a data sheet, and separate from the instruction manual, NordAmatur publish detailed spare parts specifications for their different safety valve types. Such details should feature in their instructions.

In 1979 Princess Cruises Management had been aware of the details of the safety valve components. Since then this awareness has been lost. It seems that the present management was also unaware of the nature of the guide bush, and the importance of a correct match between it and the valve spindle

Previous problems with safety valve seizures

Although it was known that the economiser safety valves were prone to seizure in 1979, this awareness seems to have evaporated.

In 1988 an MCA surveyor advised that these valves were prone to seizure within the then mandatory survey period of two years. It seems that Princess Cruises did not act on this advice, and that the MCA did not assure themselves that the recommended safety action was taken up.

At the time of the accident in 1997 the present Princess Cruises shoreside management were unaware of previous problems with economiser and safety valves, or the 1979 letter relating to procedures to avoid overpressure. They did not, furthermore, know of the agreement to survey the safety valves annually. It is possible that their records were lost because of the move of operational control from Southampton to Los Angeles, and changes in management personnel.

The management felt that ships' staff should have submitted the fleet letter for consideration when the fleet regulations were being devised in 1994 in anticipation of adoption of the ISM Code. There must have been, at this time, a breakdown in the company's management system for their inability to recall their own past concerns for the safety valves and procedures for shutting down economisers. Princess Cruises and the MCA were unable to explain why crucial safety procedures, and the reasons for them, were lost or forgotten. Without this information, the hazard associated with these safety valves could not have been assessed fully, thus seriously weakening the effectiveness of part of the safety management system since developed.

An understanding of the hazards associated with these valves would have highlighted the importance of keeping a consolidated history of defects, repair work, more frequent tests and surveys, and safety valve instructions. With these, classification society surveyors, engineers and management would be better able to judge accurately the acceptability of the safety valves for future use.

Princess Cruises' technical management took the view that freeing seized safety valves was routine maintenance, and not a defect subject to mandatory reporting. This acceptance hindered management in its efforts to assure correct and timely action being taken. A disciplined approach to report defects would have created a better awareness among engineers of their responsibilities to ensure that safety valves were maintained in good condition.

Engineers should be instructed to report faults with safety valves to the classification society or flag state, and to its shore management.

Princess Cruises should also make sure that any problem with a safety valve, and its solution, are recorded. These records should be made available to engineers and visiting surveyors. This need should be identified within the ISM Code framework. The MCA should make sure that this is done.

Classification society requirements

Boiler safety valves are approved by the classification societies and the flag state authorities. At annual surveys, LRS checks the general external appearance of the boiler and its mountings. Where a defect is found, the society will decide if a more detailed survey is required. The installation is surveyed in more detail, externally and internally, twice over a five-year cycle. Then, a safety valve, like other boiler mountings, is stripped down and its components inspected. The surveyor may require that defective components are replaced or renovated.

The safety valve is reassembled, refitted to the boiler and its lifting pressure set. LRS and the MCA have, for many years, accepted that surveyors do not have to witness the setting of economiser safety valves. The chief engineer can set them at sea and report having done so to the classification society.

Although LRS specify testing twice every five years, it is the shipowner's responsibility to ensure that devices, such as safety valves, continue to be functional between tests. Unless they are tested regularly, there is no way of knowing if they will operate effectively to guard against overpressurisation.

In May 1981, The General Committee of LRS adopted the rule which required shell-type economisers on new vessels to be fitted with safety valves having a fail-safe device. Rule 15.2.9, chapter 10, part 5 states that:

Safety valves for shell type exhaust gas steaming economisers are to incorporate fail safe features which will ensure operation of the valves even with solid matter deposits on the valve and guide. Alternatively, a bursting disc to a suitable waste steam pipe is to be fitted. These emergency devices are to function at a pressure not exceeding 1.5 times the economiser approved design pressure. Full particulars of the proposed arrangements are to be submitted for consideration.

LRS have accepted such a fail-safe device on the basis of design appraisal and type test. It described it thus:

One design of valve incorporates copper rivets holding down the valve guide. If the valve stem has jammed, the rivets will fail at a particular pressure, allowing the whole stem and valve to lift and relieve pressure on the economiser.

LRS report that the device is little used, if at all, and that most operators prefer the option of fitting a bursting disc to relieve the economiser pressure.

The introduction of this requirement indicated LRS's concern that economisers might overpressurise because of safety valve seizure. There are no records available to show why the rule was introduced, but it is probable it followed the Princess Cruises' incidents in 1979.

LRS keeps records of machinery and hull defects on a database. It is compiled from surveyors' and owners' reports, and from those found in the shipping newspaper, Lloyd's List. The jamming of safety valves is one of the defects recorded on the LRS database.

Inspection of the LRS database for safety valve seizures over a 20-year period indicates an incident rate of 0.0029 per ten-year service covering nearly 17000 boilers and associated equipment. From the reported incidents, excluding P&O ships, there has been no damage to boilers as a result.

The statistics show only a small risk of seizure, but they have to be viewed with some caution because there may be significant under-reporting to LRS. If Princess Cruises' belief that such defects need not be reported is shared throughout the industry, then it is hardly surprising that the LRS database contains such a small number of safety valve defects.

Germanischer Lloyd (GL) Classification Society requirement for boiler operation

The understanding that economiser safety valves were at risk of seizure was also recognised by GL.

The GL classification rules and instructions to surveyors refer to the German boiler regulations, the technical rules for steam boilers, (TRD) in respect to steam boiler plant on board German flagged seagoing vessels. The instructions express the need for regular lifting of safety valves to prevent them seizing. They advise that auxiliary boiler plant safety valves should be lifted briefly by the easing gear every four weeks and to ensure valves close properly after lifting.

The TRD regulations expressly state the requirements for boiler maintenance and operational procedures. These are clearly aimed to prevent incidents such as safety valve failure. The responsibility for devising testing procedures and intervals for safety valve inspection, rests with the shipowner in consultation with the inspection authority.

Extracts from the TRD 601 Sheet 1, Operation section 6, state that:

The inspection intervals shall be determined by the user who shall take the operating conditions and safety valves into consideration. ....

In the case of plants fed with demineralised water and hot water generators, safety valve operability shall be tested at least at 6-month intervals - except for power plants.

For other steam generators this interval shall not exceed four weeks....

The extent of testing and testing intervals shall be determined as being mandatory for the boiler operator by co-operation between users, manufacturers and erectors. ....

When determining tests for safety devices, the inspector shall be consulted.

The regulations provide for the extent of testing of seagoing plant to be recorded in the ship's logbook which has to be submitted to the inspector on demand. If, for any reason, there has been a change in testing procedures, it has to be recorded to avoid possible misunderstandings in the future.

The German authorities recognise the need for shipowners to take responsibility for assessing the risk of boiler operation, and for prescribing how and when testing of safety valves should take place.

Application of the ISM Code

Given the aims of the ISM Code, the marine industry needs to give careful consideration to safety valve monitoring, testing, maintenance and supervision by both the classification society and flag state. Defective safety valves should be a top priority reportable defect.

Moreover, as part of the MCA's quality audit trail of shipowners, LRS and other classification societies, it should seek assurances that appropriate action is taken when such a report is received. To this end, the timely reporting of each incident is essential to enable the underlying causes of safety valve seizure to be identified, and for the appropriate lessons to be learned.

2.5 OPERATING PROCEDURES FOR THE ECONOMISERS

One oil-fired boiler and the two economisers were operating when *Island Princess* arrived in dry-dock in November 1997. It was normal to leave the water in the economisers when in port unless repairs to them were necessary. Damage to the second oil-fired boiler after arrival in Naples rendered both boilers out of action. The economisers could not, therefore, be used.

Consequently, before starting the main engines in readiness to leave dry-dock, it was necessary to ensure that the economisers could not pressurise once they began to heat up with the passage of main engine exhaust gasses. As long as they were dry and vented to atmosphere, the possibility would not arise.

The procedures used on *Island Princess*'s economisers are discussed below.

2.5.1 Preparing and monitoring the economisers for sea-going conditions

Before sailing, the economisers were full of water remaining from the previous voyage. To avoid overpressurisation, the engineers decided to jack open the safety valves and allow the economisers to boil dry.

Emptying and venting the economiser to atmosphere for the purpose of survey or repair was standard routine, but having two economisers shut down at sea was unusual. To ensure the economisers would be well ventilated to prevent any pressure build-up as they heated, some thought and planning was necessary.

Preparing the economisers

During the morning when the ship left dry-dock, engineers in the engine room control room discussed the state of the economisers.

What was actually said is uncertain. A voice data recorder had been installed in the engine room control room and was operating, but the poor quality of the recording made it difficult to make out what was said. The sections of tape that were understood made no reference to the economisers.

The engineers have said that two meetings took place before sailing. During the first meeting at 0800 attended by the chief, second, daywork third, first engineer and the watchkeepers, the state of the propulsion plant was discussed together with what needed to be done that morning and during the sea trial. Although neither economiser was operational, it was known they contained water, and that the safety valves were likely to lift when the ship went to sea. It was agreed, therefore, that the water should be left in with the safety valves jacked open.

The economisers were again discussed at 1000, when the chief engineer met the second engineer and technical superintendent. Having assumed the economisers were empty the superintendent asked if the manhole doors had been opened. He was told they had not, but the safety valves had been jacked open.

All the engineers were experienced in economiser operation. Some had sailed on *Royal Princess*, where it was routine to drain the water every time the economisers were not in use. The starboard oil-fired boiler failed two days before the accident. With both starboard and port boilers now out of action, the engineers must have realised then that both economisers would not be operational for sea trials.

Reasons for not draining the economisers

Had the engineers on *Island Princess* decided to drain the economiser, they could have done so by connecting a hose and draining it into the dock or bilge before removing the manhole covers. This could have been completed well before sailing when the pressure of work was less. Had it been done the accident would not have occurred.

On the morning of the sea trial there would probably have been no time to drain the economisers. Venting through jacked opened safety valves must have seemed an easy option, but had fatal consequences.

A reason for not draining, offered by one senior engineer, was the need to avoid water leakage into the port boiler where contractors were working. Leakage was possible because the blowdown lines and valves interconnected the economisers and boilers.

Whatever the reason for not draining the economiser, the consequences of leaving water in them were not fully evaluated by the engineers.

Firstly, any such leakage is unacceptable. With water in the economiser, there was always the possibility of someone opening valves inadvertently, or the possibility of closed valves leaking. Electrocution was a possibility with steam and water coming into contact with electric lighting and welding equipment. There was also the possibility of scalding from hot water and steam.

The engineers did not attempt to remove these hazards, and Princess Cruises did not have any procedures in place to avoid them. Good working practice would have been to fit spectacle blanks to any feed and steam connection to the boiler being worked on.

Secondly, there was the long-term effect of allowing water to boil off in the economisers. This would adversely affect the operational efficiency and safety of the plant. As the water level lowers, the concentration of dissolved solids in the remaining water increases. Many of these dissolved solids will deposit as hard scale in the lower internal surfaces of the economisers. One effect would be to reduce the heating efficiency of the economiser. More importantly, it would aggravate any corrosion fatigue cracking already present, encourage safety valve leakage, and increase the likelihood of solids depositing on the safety valve spindles.

Monitoring the economisers

The daywork third engineer was confident he had succeeded in jacking open the safety valves. The four easing gear operating handwheels for the oil-fired boilers and the economisers were not marked to indicate which valve they operated. Therefore, before attempting to jack them open, he checked the corresponding cables connecting the handwheel to the respective valve easing gear cranks.

Confident that he had chosen the correct ones, he turned the two handwheels for the port and starboard economiser safety valves to their full extent. He inspected the safety valves before and after he jacked them open but failed to notice that the port valves were still closed.

The valve lift and therefore the movement of the short leg of the easing gear lever was only a few millimetres. However, the long leg of the easing gear lever would have moved a much larger distance as the valve opened. This movement, or lack of it, should have given sufficient clear indication of whether the valve was fully opened. However, unless the engineer regularly observed this crank, he would not know what position corresponded to valve open.

The taut operating wire can give the impression that it is open. The third engineer was probably persuaded that he had succeeded in opening the valves because the indicators at the handwheels showed them to be so.

Once it was thought the safety valves were open, nobody checked the economisers were venting safely. Had this been done, it would have been apparent that the port economiser was not doing so and that its safety valves remained shut.

From the time the main engines were started, the water in the economisers began to heat up leading to steam generation. The absence of the sound of discharging steam would have indicated one of two possible states. If the pressure gauge indicated pressure, they would not have been venting as expected. On the other hand, a zero pressure gauge reading would have meant that the steam had already discharged and the economisers were empty. In any case, their true state could, and should, have been checked.

Since nobody had foreseen the possibility of safety valve seizure, no provision had been made to check them. Checking the economisers should be a normal part of a watchkeeper's routine. All involved had assumed the safety valves had been jacked open successfully and there was no risk to the economisers. They were wrong.

A possible factor for not checking them was the increased workload associated with preparing for sea after a docking period. It was well in excess of normal watchkeeping routines, and may well have diverted the engineers' attention from monitoring the economisers. After reporting and recording the safety valves were open, the daywork third engineer was assigned to work on sewage system hydraulic valves. Other engineers were preoccupied repairing and monitoring the propulsion system and attending to the temporary oil fire boiler.

The engineers' did not believe the economisers presented a hazard. It was not the practice to monitor them as closely as other engine room machinery. Furthermore, because the economisers were positioned so high in the engine room casing, and remote from the main machinery, regular inspection was not seen to be a priority. The economiser instrumentation in the ECR was limited to waterflow measurement. There was only one pressure gauge, sited on the economisers, and the steam pressure was not recorded in the engine room logbook. These factors encouraged the perception of low risk.

- <u>Similar incidents of overpressure on other economisers in the Princess Cruises' fleet</u>

The barrelling found on the *Pacific Princess* economiser and the starboard economiser of *Island Princess* was due to overpressure. Post-accident inspection of *Island Princess*'s starboard economiser safety valves found that they would have lifted under pressure.

Overpressure is possible if the valves' lifting pressures have been set too high, This is most unlikely and, as a cause, is dismissed. Although the valve locking and sealing devices were missing, there was no reason to believe that there had been an unauthorised adjustment. There is also no reason to doubt that the valves had been correctly set after survey.

Barrelling could have occurred only when the economisers were out of service, or if their main discharge valves had been inadvertently closed with the safety valves seized. If the economisers had been in service, overpressure would have been prevented by the lifting of the oil-fired boilers' safety valves which were set at a lower pressure.

Therefore, if the possibility of inadvertent closure of the discharge valve is excluded, overpressure and barrelling must have occurred under similar circumstances to that found in this accident. That is, the economisers were shut down, not vented and still containing water. This being the case, incorrect procedures for taking out an economiser did not rest just with *Island Princess*'s port economiser.

The presence of hard scale deposits found in both starboard and port economisers indicates the possibility that venting through the safety valves to empty them occurred on a number of occasions. In a previous section of this report it is indicated that the deposits may have occurred prior to installation of the oil-fired boilers in 1989. On the other hand, the scale could have formed for reasons explained earlier in this section: that is, as the water is boiled to atmosphere, TDS concentrations increase and solids come out of solution as hard scale.

Management factors

An accident is never the result of a single action, but rather the accumulation of many events that combine together to cause whatever the incident. Very often the causal chain embraces actions, procedures and decisions that may or, indeed, may not have taken place far from the scene of the accident. The shore organisation often has a bearing on such matters, so the investigation looked at Princess Cruises' safety management system.

In many ways Princess Cruises has an effective safety management system. But an underlying weakness concerning safety valves and economisers was suspected, and the investigation focused its attention to see if these suspicions were confirmed. They were.

- The management failed to recognise the importance of adequate checks or defect reporting on critical items such as safety valves.
- With regard to the operation and maintenance of the economiser and safety valves, it did not encourage the need to properly challenge and assess situations.
- There was a lack of awareness of past incidents.
- It did not encourage an awareness of engineers to follow correct procedure.
- Problems with safety valves were regarded as routine maintenance items and not defects.

2.6 INSPECTION OF EXHAUST GAS BOILERS

The boilers were designed according to national and international fired and unfired pressure vessel codes which take into account the possibility of fatigue failure as a result of accumulated stress fluctuations during the lifetime of the boiler.

The SAFed guidelines acknowledge that flat-ended shell-type boilers are at risk of fatigue fracture. Fatigue cracking is much more likely in a corrosive environment.

Fatigue life of marine boilers is difficult to predict. One reason for this is that the anticipated level of accumulated stress fluctuations varies depending on the service pattern of the ship. An economiser of a cruise ship which enters and leaves port frequently, is subjected to significantly more stress fluctuations than, say, one installed in a container ship which makes long sea passages and fewer port visits.

The AQ7 economisers were designed for infinite fatigue life, but the investigation uncovered widespread fatigue cracking in the economisers on board *Pacific Princess* and *Island Princess*. The ruptured economiser was cracked up to 66% shell thickness. Poor boiler water had had a significant effect on fatigue crack initiation. The economiser would have eventually failed at normal operating pressure.

Rather than calling for shell boilers to be designed to fatigue design considerations, SAFed advise regular and periodic inspection using NDT examination, particularly in the area of the endplate to shell-plate attachment.

Classification societies require boilers and safety valves to be surveyed at 2½ yearly intervals, and they are generally examined externally at the annual survey of the ship. The economisers, in this case, were surveyed in accordance with society rules, but the surveys failed to detect extensive and dangerous corrosion fatigue cracks, or the tendency for the safety valves to seize well within the survey period.

Frequency of survey should depend on the age, safety record, probability of sub-standard water quality, and previous history of the boiler installation. The surveys should aim to detect, at an early stage, any deterioration or malfunction which is likely to affect safe operation.

LRS, which has itself been active in the development of the SAFed guidelines, should recognise the need for more frequent examinations of marine shell-type boilers, emphasising regular NDT inspection of areas vulnerable to fatigue cracking.

In consultation with the classification society, Princess Cruises should develop a written scheme for examining boiler installations taking into account all the factors discussed. IACS and MCA should propose to IMO that such a scheme should provide a standard in the operation of the ISM Code.

The written scheme may be updated when new problems identified could affect the safe operation of the installation. For example, where safety valves and other protection devices become ineffective because of the accumulation of boiler water deposits, more frequent checks should be made to keep them in efficient working order.

IACS and MCA should encourage that the written scheme be part of a boiler installation portfolio. It should include a statement of action taken and the cause of the defect. The aim is to help management monitor and assess safety risks and, accordingly, take timely action.

The portfolio should also include:

- written reports of boiler and safety valve examinations;
- clear and concise operating procedures needed to operate the system safely;
- special procedures in the event of an emergency;
- standards and frequency of examination of the system;
- an inventory and specifications of safety valve spare parts;
- boiler repair specifications.

Shore management should review regularly the management and effectiveness of the portfolio. Safety management system audits should be assured that the review takes place.