Nuclear Power Plant Operating Experiences

from the
IAEA / NEA
Incident Reporting System

1996-1999

AIEA IAEA

AEN NEA

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter; Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- *to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as*
- *to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.*

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

INTERNATIONAL ATOMIC ENERGY AGENCY

The International Atomic Energy Agency (IAEA) serves as the world's international governmental forum for scientific and technical co-operation in the peaceful use of nuclear technology. Established as an autonomous organization under the United Nations (UN) in 1957, the IAEA represents the culmination of international efforts to make a reality of US President Eisenhower's proposal in his "Atoms for Peace" speech to the UN General Assembly in 1953. He envisioned the creation of an international body to control and develop the use of atomic energy. Today, the Agency's broad spectrum of services, programmes, and activities is based on the needs of its 131 Member States.

Technology transfer

The Agency works to foster the role of nuclear science and technology in support of sustainable human development. This involves both advancing knowledge and exploiting this knowledge to tackle pressing worldwide challenges – hunger, disease, natural resource management, environmental pollution, and climate change. A substantial part of the Agency's work relates to nuclear power, including its safety and waste management, and ensuring that nuclear technology is being used only for peaceful purposes.

Where appropriate, the IAEA facilitates transfer of nuclear technology to Member States for use in medical, agricultural, industrial, water management, and other applications. Many of these programmes contribute directly or indirectly to the goals of sustainable development and protection of the environment set out in "Agenda 21", of the 1992 UN Conference on Environment and Development. The Agency also has two scientific laboratories where training and research are performed in support of technical co-operation and assistance activities. Many of these activities are conducted in conjunction with the Food and Agriculture Organization (FAO). The Agency co-operates in a joint division with the FAO, promoting applications of isotopes and radiation in food and agriculture. This includes such areas as plant breeding and genetics, insect and pest control, soil fertility, irrigation and crop production, animal husbandry, and food preservation.

Nuclear safety

The future role of nuclear energy depends on a consistent, demonstrated record of safety in all applications. Although the IAEA is not an international regulatory body, its nuclear safety efforts are directed towards creating multilateral, legally binding agreements, which are increasingly important mechanisms for improving nuclear safety, radiation safety, and waste safety around the world. IAEA safety recommendations are used by many countries as a basis for domestic standards and regulations. Codes of practice and safety guidelines have been developed for the siting, design, operation, and quality of nuclear power plants. To strengthen worldwide operational safety further, the Agency performs safety evaluations on request, including on-site review of nuclear power plants by international expert teams.

Non-proliferation of nuclear weapons

As part of the global effort to prevent the proliferation of nuclear weapons, the IAEA verifies that nuclear materials are not diverted away from legitimate peaceful use for military purposes. Once a Member State becomes a party to a safeguards agreement, the Agency's inspectors monitor all declared nuclear material through on-site inspections, remote surveillance, and record verification. Without this systematic safeguards system, trade and technology transfer of nuclear applications would not be possible. To date, there are 223 safeguards agreements in force with 139 states. The IAEA safeguards role is being further strengthened to allow greater detection of any potential diversion of nuclear material.

REPORTING GUIDELINES

Feedback from safety related operating experience for nuclear power plants

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EXECUTIVE SUMMARY

Incident reporting has become an increasingly important aspect of the operation and regulation of all public health and safety-related industries. Diverse industries such as aeronautics, chemicals, pharmaceuticals and explosives all depend on operating experience feedback to provide lessons learned about safety.

The Incident Reporting System (IRS) is an essential element of the international operating experience feedback system for nuclear power plants. IRS reports contain information on events of safety significance with important lessons learned. These experiences assist in reducing or eliminating recurrence of events at other plants. The IRS is jointly operated and managed by the Nuclear Energy Agency (NEA), a semi-autonomous body within the Organisation for Economic Co-operation and Development (OECD), and the International Atomic Energy Agency (IAEA), a specialised agency within the United Nations system.

This report highlights important lessons learned from events reported to the IRS over the period of July 1996-June 1999. A total of 342 events were reported by the participating countries during this time. Several areas were selected in this report to show the range of important topics available in the IRS. These include several different types of failure in a variety of systems, as well as experience of human errors in combination with system failures. It is important that sufficient national resources be allocated to enable timely reporting of events important to safety, and to share these events in the IRS database.

This report is intended to provide general information for senior officials in industry and government who have decision-making roles in the nuclear power industry.

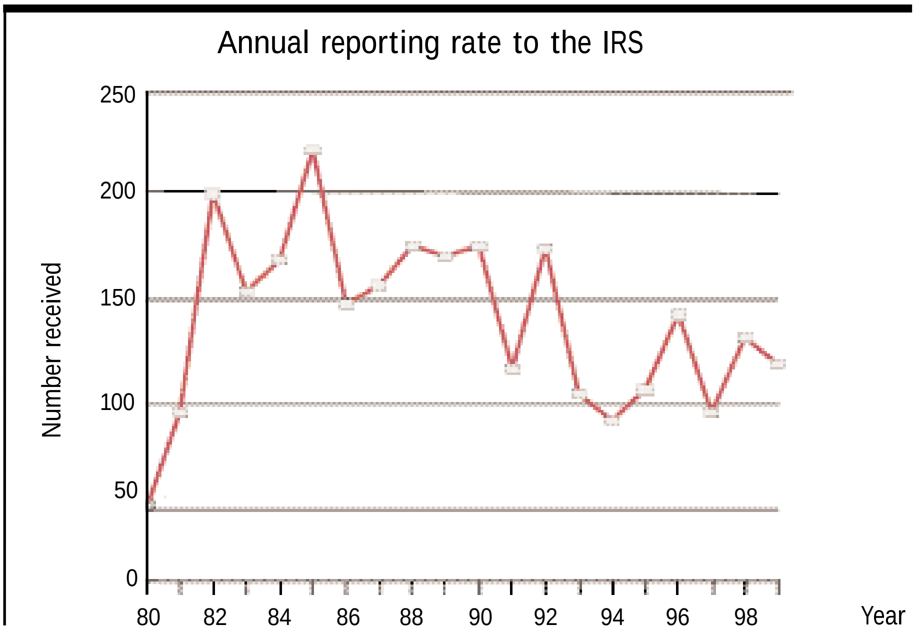
1. THE INCIDENT REPORTING SYSTEM

The IRS has been established as an efficient system for exchanging important lessons learned from operating experience gained in nuclear power plants. Reporting is based on the voluntary commitment of the participating countries.

Each participating country contributes to the programme by reporting events or conditions and benefits by receiving operating experience feedback. Events reported to the IRS are those of safety significance for the international community in terms of causes and lessons learned.

The IRS is jointly operated and managed by the Nuclear Energy Agency (NEA), a semi-autonomous body within the Organisation for Economic Co-operation and Development (OECD), and the International Atomic Energy Agency (IAEA), a specialised agency within the United Nations system.

The main objective of the IRS is to assure proper feedback on events of safety significance on a world-wide basis to help prevent occurrence or recurrence of serious incidents or accidents.



The IRS is an important source of information for regulators and their technical support organisations, providing insights on important international operational experience for oversight and licensing purposes. Operators also benefit from the quality and completeness of IRS reporting.

Both the NEA and the IAEA have assigned groups that meet annually and discuss the safety relevance of such events. These groups take part in in-depth discussions of recent important events. Conclusions and recommendations from in-depth discussions are extremely valuable to the nuclear community in helping to enhance the safety of plants in operation.

The annual reporting rate since 1980 is shown in the graph. At present, some 100 events are reported per year, from a family of about 500 reactors world-wide. The reporting rate has generally declined over the past 15 years. At the outset of the IRS it was thought that a rate of about 0.5 reports per reactor year was a reasonable goal. The current rate is of the order of 0.25 reports per reactor year. The test of significance is not so much the quantity as the quality; that is, the goal is to ensure that the more important events are fully reported. Based on meetings and other communications, it is felt, overall, that the more important and significant events are contained in the IRS database.

The IRS contains more than 2 800 reports gathered from the participating countries over the past 20 years. Recently it has been improved to offer an enhanced system of data storage and information retrieval. Events are reported by the participating countries and transcribed to a CD-ROM, which is constantly updated and sent to the national IRS co-ordinators by the IAEA on a quarterly basis.

Participating countries

Argentina
Armenia
Belgium
Brazil
Bulgaria
Canada
China
Czech Republic
Finland
France
Germany
Hungary
India
Italy
Japan
Korea (Republic of)
Lithuania
Mexico
Netherlands
Pakistan
Romania
Russian Federation
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Ukraine
United Kingdom
United States of America

2. CONCLUSIONS DRAWN FROM THE IRS DURING THE REPORTING PERIOD

2.1 Experience with reactor core shroud cracking

A boiling water reactor (BWR) has a metal structure inside the reactor vessel known as the core shroud.

The core shroud has several purposes, including i) serving as a barrier between the core and the annulus, thus separating the flow in those two regions, ii) providing vertical and lateral support for the core plate, top guide and shroud head, and iii) serving functions associated with in-vessel emergency core cooling system (ECCS) distribution.

Summary of reported events

The first cracks in the core shroud were reported to the IRS in 1990. Since then, similar cracks were detected in subsequent inspections in more than ten plants.

When crack indications have been observed, ultrasonic tests were carried out for evaluating the depths of the cracks. Cracks were found within the base material or in the heat-affected zone of the welds connecting the support ring to the shroud. Further circumferential cracks were found in the lower part of the shroud.

Safety significance

The shroud is important for safety during both normal operation and postulated accidents. The structural capacity of the shroud in case of a seismic event, or a large pipe break, is reduced when it is in the cracked state.

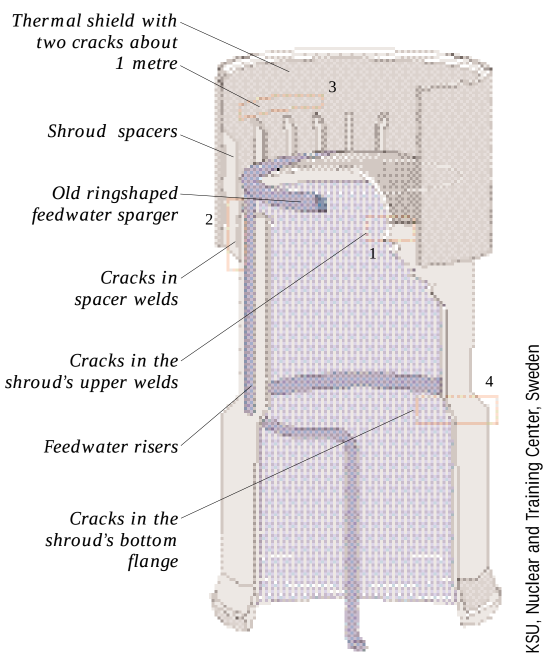
The perceived risk importance is relatively low, mainly based on the slow propagation rate of the crack and monitoring during maintenance and inspection.

Lessons learned

The causes for the shroud cracking failures included high carbon content in the material, unfavourable heat treatment and unfavourable weld procedures. This led to intergranular stress corrosion cracking.

Owners and regulators are aware of this cracking experience and are proceeding towards shroud inspection, including short-term corrective actions and long-term solutions. Many owners are considering a remedial shroud replacement with a new shroud made of materials less prone to this type of failure. Successful replacement has already been made in some participating countries.

Core shroud with cracks



Some construction materials for the core shroud are particularly susceptible to intergranular stress corrosion cracking (IGSCC).

Adequate heat treatment and an appropriate welding process have to be applied to construction materials used for core shroud to make them less sensitive to IGSCC.

2.2 Experience with unavailability of components of a safety system

Nuclear power plants are equipped with safety systems to prevent or cope with accidents should they occur. It is a part of the "defense-in-depth". Safety systems are designed with two or more trains of equipment, each capable of performing the safety function.

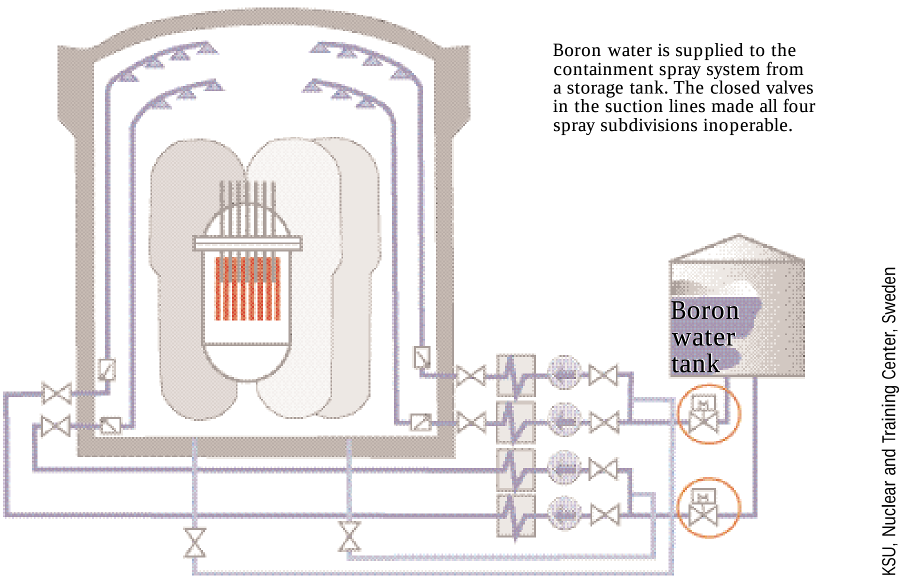
Summary of reported events

The containment spray system is a safety system which cools the containment and lowers its pressure in the unlikely event of a release of hot fluids from a pipe or failed valve.

During normal operation a containment spray pump was found to be inoperable. A failure was also found in a second train due to deficiency in the power supply to the pump motor. In this case there were three spray trains in the system.

In another case, all four trains were inoperable for a short period of time due to two closed valves as illustrated in the figure.

Illustration of a common cause failure
in a containment spray system due to closed valves



Safety significance

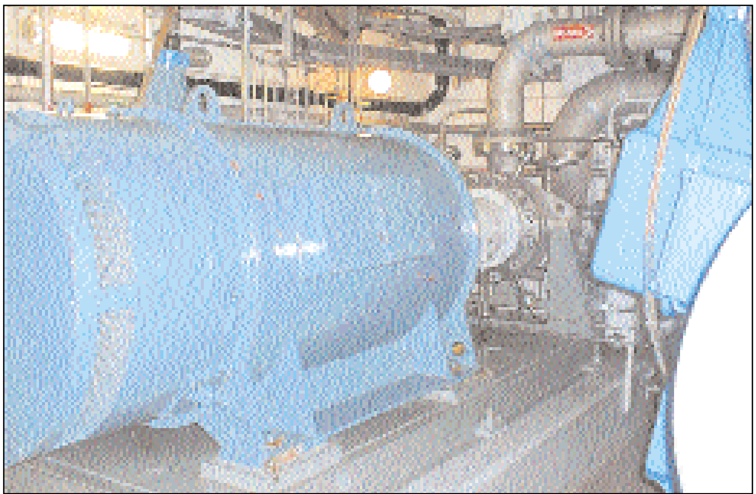
These events are considered safety significant as they illustrate the possibility of having hidden or undetected failures in one safety system affecting other safety systems further down the line.

Lessons learned

Deficiencies were identified in organisation, work planning, elaboration and quality control of the technical documentation and personnel training.

One reporting organisation has several similar reactor units, and previous difficulties occurred in the past in these systems, with similar causes. Lessons learned included that the reporting organisation should analyse its existing technical documentation for the maintenance of the safety system equipment in accordance with the requirements.

Other lessons from this event involved the organisational aspects of operating, maintaining, testing and documenting safety systems.



Ringhals, Vattenfall AB, Sweden

Containment spray pump.

Through events of this type, the international nuclear community is reminded of the actual and potential importance of organisational factors and configuration control for plant safety, as well as of periodical testing of safety systems.

2.3 Experience of inadvertent control rod withdrawal

Reactor control and safety depends on the use of neutron-absorbing control rods. During plant operation, the rods are extracted gradually from the reactor core to produce power. In response to a variety of safety signals, the rods are automatically reinserted to decrease power.

Summary of reported events

During a normal reactor start-up, the operating staff decided to terminate the start-up procedure and selected a group of control rods to be inserted back into the reactor core. However, due to errors in maintenance of some motors in the rod drives, six of the motors ran backwards and withdrew the rods, instead of inserting them.

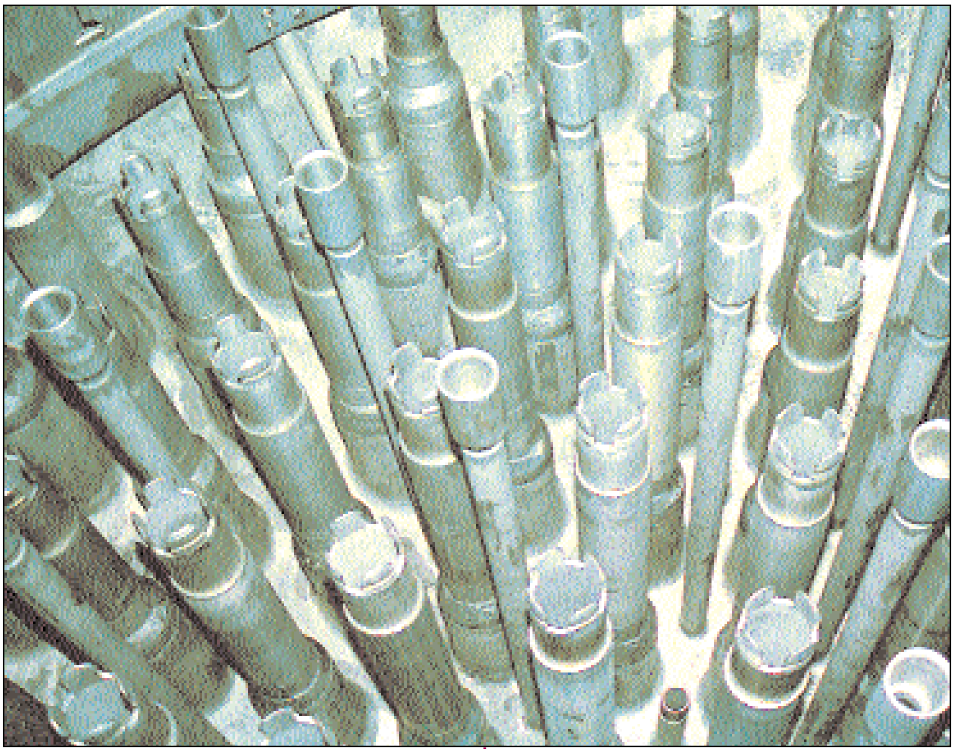
Safety significance

There are backup systems to insert the rods quickly (i.e. trip or scram) before there are serious consequences. Inadvertent rod withdrawal is anticipated in the safety analysis, and serves as a design basis for the safety systems. However, the implication of this event is broader.

Lessons learned

The cause was assigned as a maintenance error in coupling the power to the bus that supplied the drive motors. Corrective actions included a review of the maintenance procedures and practices, a review of the process of verifying the operability of components after repair and replacement, and improvements in the quality assurance programmes.

Events like this led to a decision to perform generic studies in several countries on the operability of components and systems after maintenance, repair and replacement. It is common for countries to pool knowledge to come up with recommendations to improve safety.



OKG, Aktiebolag, Sweden

Pins in the bottom of a pressure vessel for guiding control rods into the reactor core.

Verification of operability of components after repair and replacement must ensure the availability of a system.

2.4 Experience with control rod problems

Reactor control rod elements must remain able to enter the core automatically in order to shut the reactor down on demand. The design takes into account the possibility that one such element might fail to insert on demand, without consequence for plant safety.

Summary of reported events

Several events have been reported with control rod elements inserted at a rate slower than usual, or inserted only partly. The dominant cause is that fuel assemblies were found to have been deformed, such that there was not a straight, smooth path for the insertion of the control rods.

One reported event on failure to insert a control rod fully in a boiling water reactor concerned the swelling of the control rod such that there was interference with the neighbouring fuel housing. Only one control rod, out of many in the design, had difficulties.

In one instance there was a report of cracking in some of the control rods which produced the possibility of some of the control material (boron carbide) being dissolved into the primary coolant. Compensatory action, including eventual replacement of the rods with a better design, was prescribed by the regulatory body.

Safety significance

The control rod insertion failures considered in these reports were relatively mild. Nonetheless, these control rod difficulties are considered important in that, unchecked, a more serious situation could develop.

Lessons learned

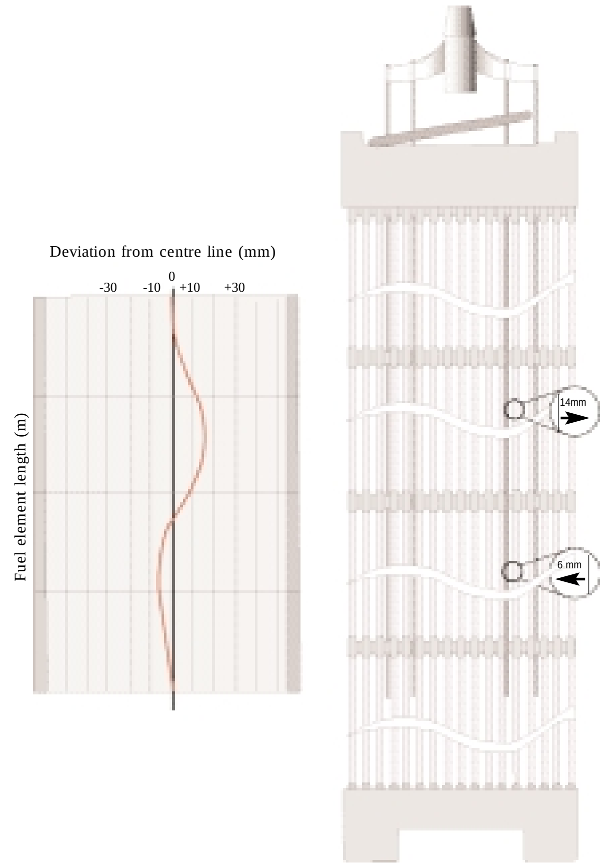
The early announcement of the phenomenon induced a systematic monitoring of control rod insertion on a world-wide basis. Various reactor facilities also reported difficulties with rod insertion.

In PWR-type reactors where the problem occurred, a safety assessment of each plant situation was conducted before continuing operation.

A refined analysis showed that the excessive bowing of the fuel elements was ultimately the result of a reduction of the overall rigidity of the fuel assemblies. This was caused by successive fuel design modifications. The reduction of rigidity of the fuel assemblies could also induce bowing of the whole reactor core, which could then amplify the phenomenon.

Modifications of the fuel assembly design were performed and strategies developed to take care of the overall reactor core bowing.

Illustration of bent fuel elements causing delayed control rod insertion



KSU, Nuclear and Training Center, Sweden

Introduction of design changes in one component may induce unexpected problems. Plant owners must be aware of problems resulting from design changes.

2.5 Experience with diesel generator failure to start

Nuclear power plants have on-site emergency power systems to cope with the loss of station power. Usually the source of emergency power comes from redundant diesel generators. The trains are redundant to the extent that they do not all need to work in order to provide the safety function.

Summary of reported events

Two failures to start diesel generators with potential safety concern were reported. There was a failure in a valve in the air start system, and more importantly, there was a failure due to a substitution in the type of diesel fuel used, which could result in the failure of all of the diesels (an example of what is known as common cause failure).

In another case, two (of four) diesel generators were found to be unavailable. However, the design basis of the plant was that one diesel alone will allow the plant to be shut down. In addition, the two unavailabilities were not related, so this was not a case of common cause failure.

Safety significance

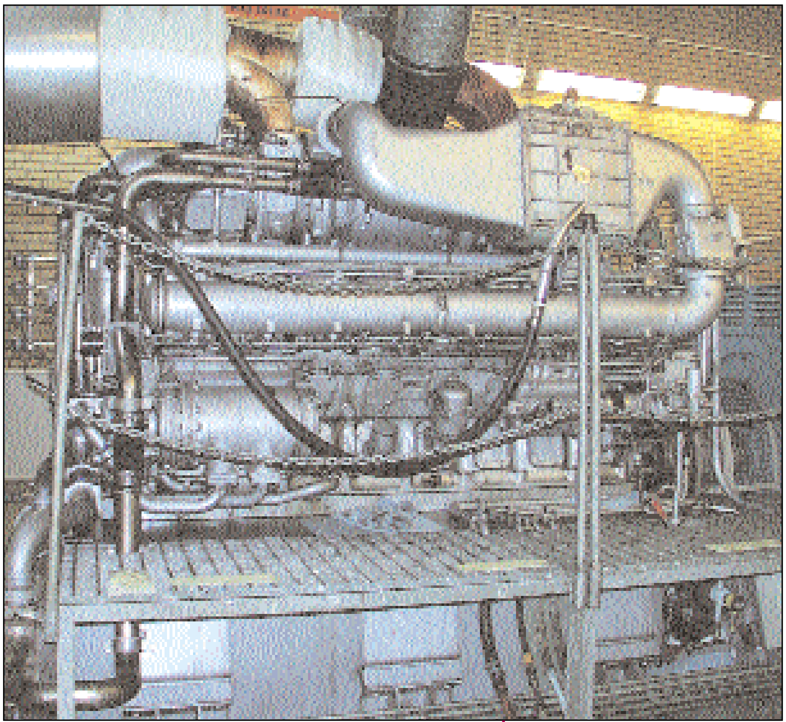
In almost all cases the emergency power is from diesel generators. The onsite emergency power is needed when other power sources are lost. In many cases, the dominant contribution to risk is attributable to the loss of all power (i.e. both offsite and onsite sources).

The safety case for the design usually postulates a highly reliable onsite power source. If the high reliability comes into question, then the design adequacy could also come into question. Hence, it is important to monitor trends in emergency power reliability, and to act quickly when the reliability is reduced.

Lessons learned

The events with common cause failure for all of the diesels are of most concern.

An interesting aspect of the event involving the fuel is that the new diesel fuel had been purchased to comply with the low sulphur content requirement set down in national legislation to protect the environment. As it turned out, sulphur reduction also reduced the lubrication process of the diesel fuel, and this ultimately led to the blocking of the fuel injection pump for the diesel engine. The potential for common cause failure for all diesel engines, illustrated here by this event, is always of concern. Also illustrated by this event is the necessity for a comprehensive test and inspection programme and a corrective and preventive maintenance programme.



Barsebäck Kraft, Sweden

Back-up diesel generator.

Potential common cause failures are important to detect and to prevent. Many incidents are related to changes and modifications. Changes need to be analysed in detail before their implementation.

2.6 Experience with loss of integrity of primary system piping

The loss-of-coolant accident (LOCA) has been a traditional design-basis event for nuclear power reactors. Redundant safety systems are provided to replenish water to the reactor core, should there be a LOCA.

Summary of reported events

Experience from several events involving degradation in the primary system pressure boundary, including connecting systems, was reported. In some cases there was potential for a significant primary system leak that could not be isolated by closing a valve.

In one case there was a preliminary report of a failure in the low pressure piping of the residual heat removal system, resulting in leakage of the order of 30 m^3/hour. The failure mode had not yet been diagnosed in the preliminary report, but the plant was in the initial commissioning mode.

Another reported event involved a loss of coolant from the primary system due to the opening of an interconnecting path to another system, while the unit was being shutdown. More than 40 000 litres were drained in about a minute, until the pathway was closed by closing the interconnecting valve.

Safety significance

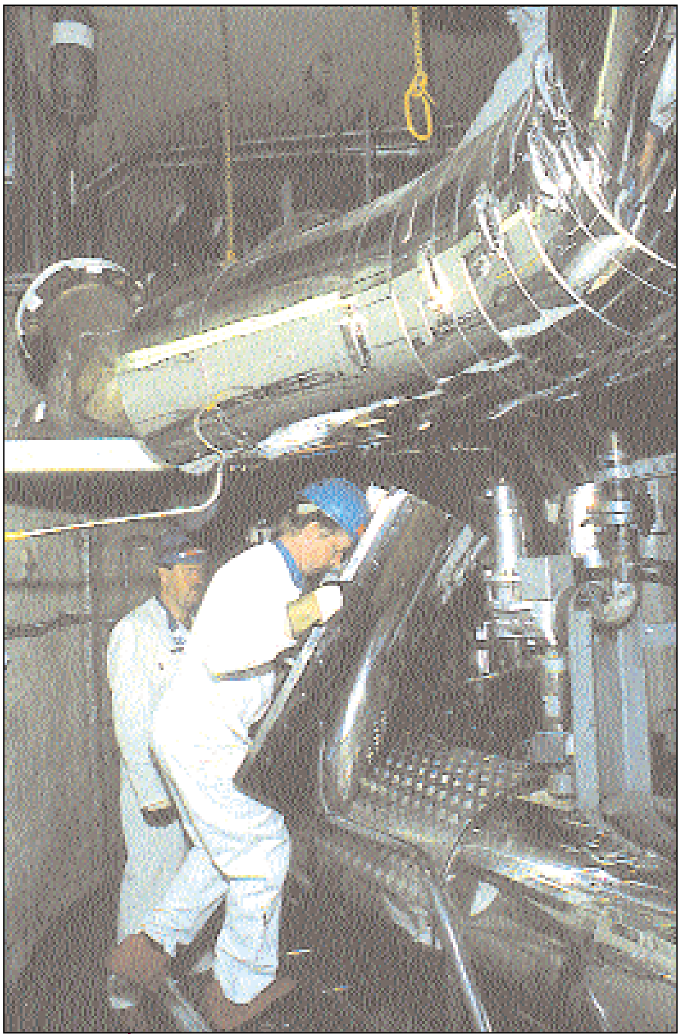
The loss-of-coolant accident for most designs assumes a rupture of size up to the largest connecting pipe in the primary coolant system. The design basis usually provides for sufficient redundant equipment such that there will be little or no fuel damage, and the decay heat can be adequately transported to the ultimate heat sink. In this event, the emergency core coolant system (ECCS) functioned as designed and there was no fuel damage.

There has never been a major rupture in large piping of the reactor coolant systems.

Lessons learned

The event which was caused by a valve failure and pipe break incident resulted in leakage from the reactor coolant system. Causal analysis revealed a less than adequate design of the relief valves and piping, and thermal ageing of material. Corrective actions included a new over-pressure system, along with component replacement in the valves, and a more appropriate surveillance programme of components.

The event which involved the unintended system interconnection and consequent draining of the primary coolant system resulted from parallel tasks in progress that had not been adequately co-ordinated.



OKG, Aktiebolag, Sweden

Piping and insulation in the reactor containment.

The events highlight the importance of in-depth analysis of unusual events, in order to correct situations not considered in the original design.

2.7 Experience with piping failures as a result of wall thinning and thermal fatigue

Piping becomes "thinner" due to combined effects of flow velocity together with unfavourable materials and water chemistry. This phenomenon is called wall thinning, or flow-assisted corrosion.

Thermal fatigue due to stratification and mixing of hot and cold water is a recurring phenomenon, but with a relatively low frequency.

Summary of reported events

Piping degradations due to wall thinning and thermal fatigue were reported. The initial wall thickness of piping, which originally had some design margin, was observed by in-service inspection to have thinned to such an extent that in some cases it resulted in the sudden rupture of the pipe.

There were also reports on cracks and leaks caused by periodic mixing of hot and cold water (thermal fatigue). There was an event involving cracking and leaking of a pipe elbow due to thermal fatigue in the letdown system of a PWR.

EdF, France

Thermal fatigue crack.

Safety significance

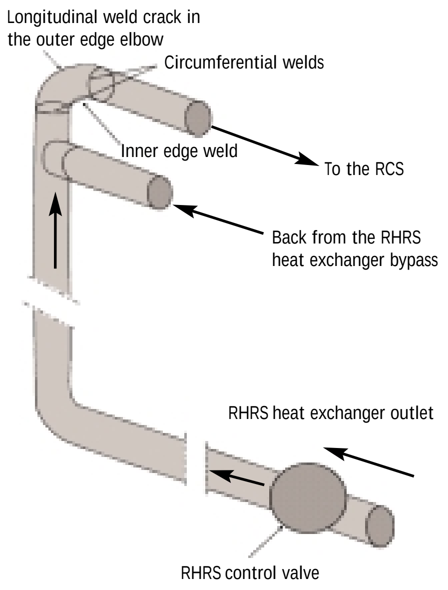
A pipe failure in a single train of equipment should not result in core damage or fission product release, as there is redundancy in design. A pipe failure, however, does pose a higher risk than desirable. Further, some pipe failure mechanisms occur at the system level, which means that the system function is degrading. This is of greater risk significance than degradation at the train level, where an additional redundant train (or trains) is available.

Lessons learned

There is excess pipe material provided in the design, which provides some margin in the thinning of some primary heat transport piping. The cause of the thinning was flow-assisted corrosion. More work is now in progress to understand the actual thinning mechanism, and to determine the appropriate re-inspection intervals. Changes may be needed in process and chemistry control.

Another report, of a generic nature, dealt with a review of industry efforts to manage thermal fatigue, flow-accelerated corrosion, and water hammer damage to sections of PWR feedwater nozzles, piping and feed-rings. Reports on these failure mechanisms have been provided to the IRS over at least the past ten years.

Thermal fatigue caused by mixed hot and cold water



These failure mechanisms can be managed through careful and thorough analysis, inspection, monitoring, mitigation and replacement techniques.

2.8 Experience with a circuit breaker explosion

Electrical circuit breakers are provided throughout nuclear power plants, in both safety and non-safety systems. In most cases there are rooms, called power distribution rooms or circuit breaker rooms, where electrical power equipment is located.

Summary of reported events

This report provided information on a failure in an electrical system circuit breaker that resulted in the explosion of an oil-air mixture. This explosion caused considerable damage in the room that housed the breaker. This event revealed a new failure mechanism for circuit breakers, and illustrated the potential for unanticipated system interaction.

Safety significance

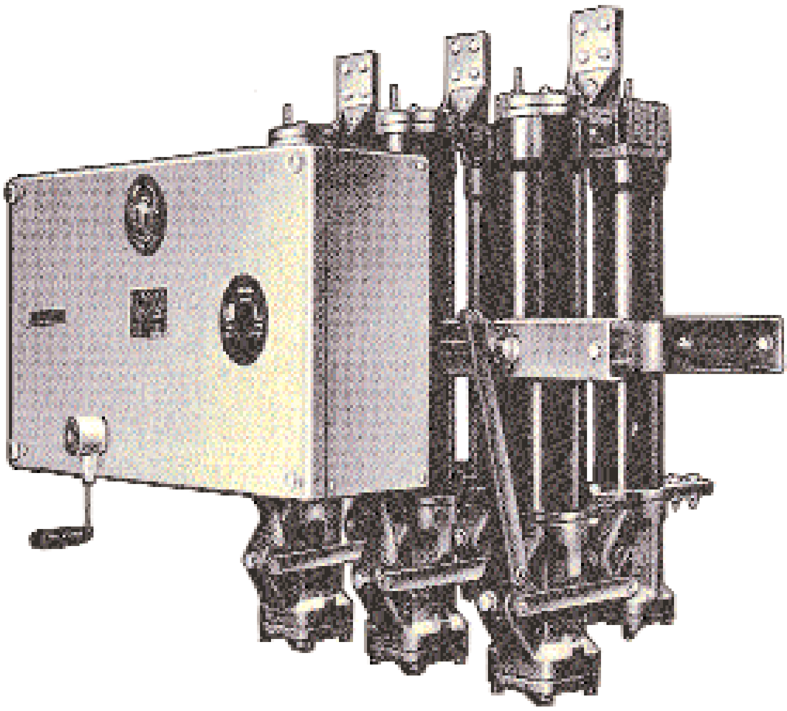
Failure of a single breaker is considered in the design basis. However, the design basis usually does not consider the potential for the breaker to fail in such a manner. The safety significance is such that one failure mechanism could be the common cause for multiple failures.

Lessons learned

The cause of the event was that the breaker did not open properly, causing the housing to overheat (due to arcing inside), and as a result, the housing failed. The failure mode was unanticipated.

The lesson learned from this event was internal explosions are possible in some cases. Re-evaluation of the safety case could be necessary for other plants. An explosion like this can challenge the fire protection system of any plant.

Typical electric circuit breaker



Operating experience illustrates the need to evaluate unexpected phenomena in the safety case for the plant.

2.9. Experience with valve problems

A nuclear power plant may have several thousand valves. The valves are used for isolation purposes and for flow control. Many safety systems have isolation valves that may change their position during a challenging transient. Pressure locking due to thermal binding is the term used when the liquid inside the valve body heats up and pressurises the valve discs.

Summary of reported events

Valve failures are recurrently reported to the IRS. In several instances, a safety-related valve was not able to operate on demand since water, trapped inside the valve body, had heated up, and raised the pressure on the valve components so that the motor-operator was not powerful enough to overcome the pressure force.

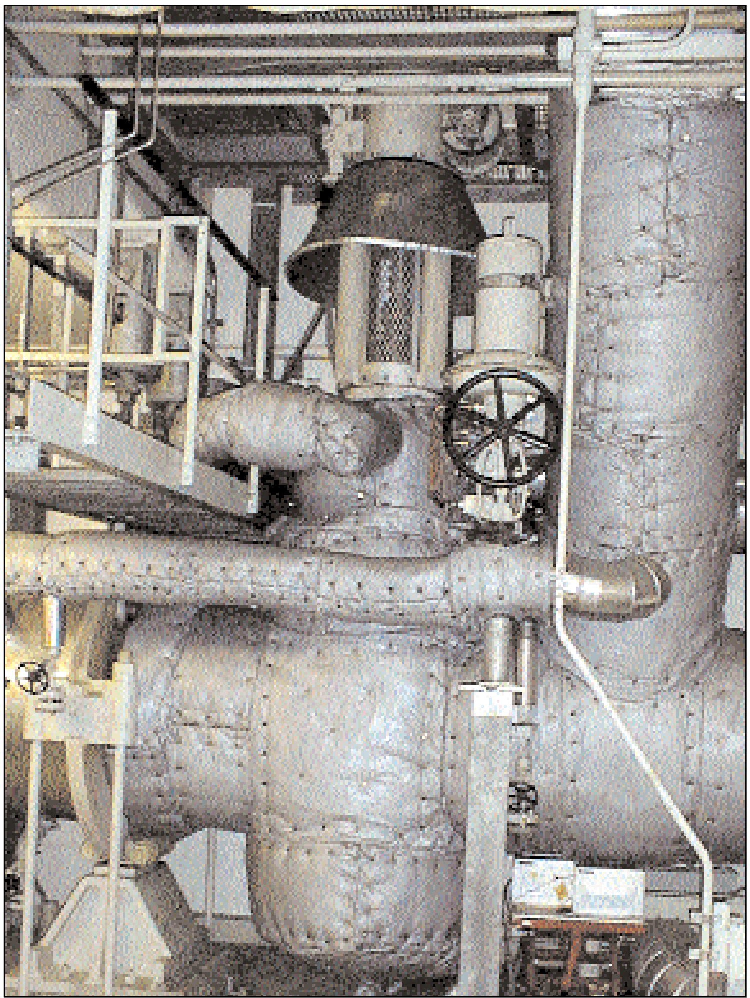
Safety significance

Failure of a valve can cause the failure of a train to operate as designed. If the safety system has redundancy, then such a train failure reduces (or eliminates) the inherent redundancy. One concern would be that the failure mode would be common to the same type of valves in similar trains, and thus be a common cause failure mechanism. Then, the loss would be at the system level, instead of the train level.

Lessons learned

Plant operating procedures did not call for an operability test to be performed under hot conditions, and thus the inoperability was not discovered until the valve was examined as a result of a request by the regulatory authority. This type of failure has occurred in a number of plants over the past years.

In another instance there was a planned surveillance test where a valve would not open due to thermal binding. It was found that a relief hole had not been drilled. Among other things, this illustrates the value of tests and surveillance activities.



Ringhals, Vallenfall AB, Sweden

Main steam isolation valve.

Valve failures are recurrent problems and have potential for common-cause failures. Continuous improvements are needed through tests and surveillance.

2.10 Experience with vessel head penetration cracks

The upper head of a PWR has penetrations for the control rod drive mechanisms. Over the last several years a class of designs has been affected by some cracking and leakage around vessel head penetrations.

Summary of reported events

Reports were received on the cracking of the reactor vessel upper head internals, around some of the control drive penetrations. This phenomenon has been observed earlier.

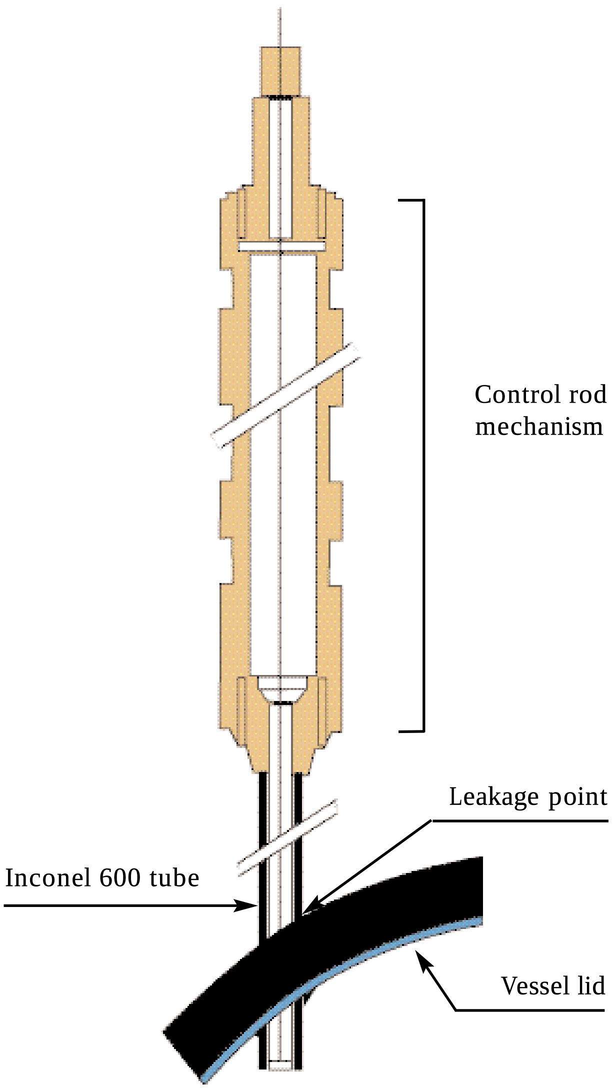
Safety significance

Cracking and leakage through the reactor pressure boundary is of concern, but not necessarily of high risk significance, provided it is detected and the reactor is shut down for inspection or repairs. It is generally agreed that crack growth is quite slow, and that this is a low-risk scenario. The worst case could, hypothetically, be an instantaneous failure at the connection to the vessel, which would lead to a small-break LOCA, and could result in an ejection of the control rod, which is attached to the drive in question. Rod ejection is included in the safety case.

Lessons learned

In this instance, the inspection showed during two consecutive inspections that the vessel continued to experience cracking at the vessel head penetrations. The short-term actions were to remove some cracks and seal some penetrations. Ultimately the vessel head was replaced with a new one.

Control rod penetration in vessel lid



In-service inspections must focus on sensitive areas of the pressure vessel.

2.11 Experience with operational events which include human factors considerations

Summary of reported events

Several of the reported events concerned human factors.[2] There was a transient involving the depressurisation of the reactor coolant system of a pressurised water reactor. A control room operator chose, contrary to procedures, to block a safety circuit that would have automatically started the high pressure emergency core cooling systems. Blocking the emergency core cooling system (ECCS) was one of the causes of the event at Three Mile Island, and is of continuing concern.

One report dealt with power oscillations at a boiling water reactor. Such oscillations have been reported in several countries over the past 15 years. In this instance the operating staff recognised the oscillations and shut the reactor down.

Safety significance

Blocking the emergency core cooling system (ECCS) is generally contrary to procedure, especially if the ongoing event has not yet been diagnosed. Although the design is tolerant to a single failure in a safety system, blocking generally renders all trains in a system inoperative, and is thus more than a single failure. The plant safety depends on a good design, quality construction and station operating staff faithful to the procedural aspects of operation.

Boiling water reactor power oscillations are not thought to be of high risk or safety significance, but are supposed to be either precluded by design, or detected and suppressed.

Lessons learned

The plant operators mistakenly thought that there was excess steam demand from the secondary side (steam side). The reactor ultimately tripped on low pressure. As pressure continued to decrease, the reactor operators blocked the auto-start signal for high-pressure makeup (i.e. the ECCS). After a few minutes, plant supervision noticed the situation on the control boards, and ordered that the blocking be disabled. At that point in the scenario, the high-pressure injection auto-initiated, as the bypass was no longer in place.

A post-incident review of the situation revealed that the operations staff lacked formal guidance on blocking limitations. An appropriate control of engineered safety features is an essential element of reactor safety. For the present event, there were no adverse results such as fuel failure.

The event involving power oscillations showed that more restrictions were necessary for power operation with respect to the combinations of reactor power, recirculation flow rate and control rod positions.

Halden Hammlab research facility for human factor research.

Human factor considerations must be addressed on a continual basis.
Systematic use of procedures should be an element in operator training.

3. IN-DEPTH DISCUSSIONS

The Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) sponsor annual meetings where delegates from participating countries gather to discuss recent events of special interest; to have in-depth discussions on selected topics; to review the operation of the IRS; and to discuss and evaluate generic studies. This section contains a summary of in-depth discussions on three topics that were of special interest during the reporting period.

Topic No. 1: Maintenance during operation

There is a positive aspect to maintenance during operation: defects can be recognised and repaired. From a negative point of view, the item under maintenance is unavailable on demand. The maintenance problems were analysed using several examples.

Common agreement was reached among the specialists on the following points:

- There should be better formats for organising the maintenance during operation.
- Risk analysis of the maintenance action should be performed to estimate the risk versus the benefit.
- The balance between maintenance during outage versus during operation should be studied rigorously, including the use of risk techniques.
- Maintenance during night shifts and weekends have fewer competent staff available.
- Maintenance activities during operation may have different organisations for support than those during outage.
- The operation period should not be overloaded with maintenance efforts.

Topic No. 2: Conflicts between safety and availability

Operation of the plant can, from time to time, produce a conflict between safety and availability, although these two facets are not necessarily mutually exclusive. For example, the need to produce power in an efficient and economical manner can lead to shorter refuelling and maintenance outages, and increased on-line maintenance and surveillance. The pressure to achieve higher availability can be at cross-purposes with achievement of the desired safety margin.

Another example at a reactor of the boiling water type was that a control rod drive had some difficulty in inserting a control rod. Instead of discerning the root cause, the operating staff increased the hydraulic drive pressure so that the rod drove in on command. Later, the problem reoccurred, and this time several drives were affected. After shutdown, a deeper investigation revealed some small metallic particles were collecting and causing friction. These particles came from earlier maintenance work on the reactor.

These events illustrated situations involving conflicts between the desire to maintain power production and the need to maintain adequate safety.

Topic No. 3: Safety significant events within operating limits and conditions

In general, plant safety is controlled by the specification of operating limits and conditions (OL&C), within which the plant must operate. However, from time to time events of safety interest occur even though the OL&C are not exceeded. At one meeting there was a discussion of some examples of such operation. They included:

- primary system leaks, within the capacity of the normal makeup system;
- increase in the drop time of control rods;
- inadequate level in the raw water system, with problems in the level measurement system;
- diesel generator start-up time increasing;
- low pressure in an accumulator of a PWR;
- water hammer in a fire protection system;
- loss of offsite power due to a tornado;
- clogging of pump waterways in a circulating water system (including the essential service water);
- clogging of fuel assemblies;
- inadvertent opening of a safety-relief valve in a BWR.

In these cases the reactor remained in compliance with its OL&C. These events were interesting in that in some cases they could have been a precursor to a more significant problem.

4. GENERIC STUDIES COMPLETED

Generic studies are carried out on topics of general interest where there may have been similar events in several of the participating countries. Generic studies are organised at the yearly meeting and developed by consensus. A study usually takes two or three years to complete. The studies listed below were completed during this reporting period.

Study No. 1: Latent failures of safety systems[3]

The safety concern that prompted this generic study was that, on the basis of reports to the IRS and to the national reporting systems, there were a significant number of latent failures in safety systems that remained undetected over many years of operating time. These hidden defects were present, in some cases, since the initial plant start-up. Also, latent failures may be introduced through maintenance activities or through modifications in the plant.

The scope of the report was to review the failures that were detected, the methods of discovery of the failures, the corrective and preventive actions and the response of the regulatory body. Several countries participated in this generic study.

> A latent failure is when equipment remains inoperable, or is unable to fulfil its intended function correctly, for an extended period of time.

The events that were considered during this study involved a broad class of systems and a great variety of failures. Some failures, the report concluded, could have been detected earlier by more complete surveillance, or could have been prevented by better monitoring and more effective post-maintenance testing.

The report concluded that:

- Existing test programmes should be improved.
- The implementation of modifications, and subsequent requalification, should be assessed.

- Post-maintenance testing requirements should be established to verify the operability of the system.
- Appropriate instrumentation, monitoring or diagnostic techniques for trending component performance should be implemented.

Study No. 2: Operating experience in computer-based systems[4]

A continued expansion of digital technology in the nuclear power industry has been observed. An important part of a failure analysis is the feedback of operating and maintenance experience, and that was the object of this study.

Several participating countries contributed experiences on failures in digital equipment. Different failure modes for digital technology were identified. For example, digital equipment is more sensitive to random electrical "noise" known as electromagnetic interference (EMI). This could, in some cases, be attributed to poor grounding and poor electrical connections.

Study No. 3: Role of simulators in operator training[5]

The generic study considered the current practices and on-going research projects for the use of simulators in the reactor operator training programmes. The study was based on a survey of 25 different organisations (training centres, utilities and regulatory bodies) representing 11 countries.

Some conclusions reached by this study include:

- Simulators play an important role in training. New developments include the use of specialised, compact simulators installed in work stations.
- There are significant differences in the manner in which simulators are used by the participating countries for training, both by the utilities and the regulatory bodies.
- In some cases risk assessment has been used to select important training scenarios, but many countries have not yet done so.
- Root cause analysis from the study of operating events is not sufficiently detailed to conclude whether training deficiency is a contributor to the event.
- Some unsolved simulator training issues include team work; stress; severe accident training; and shutdown and low power operation training. These issues are subjects of ongoing research and development.

However, there was a concern that the flow of information from research centres to the end users (utilities, regulatory bodies) was not as fast as it could be, and should be. One recommended solution was to involve a practitioner of human behavioural sciences in the mainstream of operator training.

Study No. 4: Foreign material intrusion in plant systems[6]

Recent exchanges of operational safety experience among countries, within the framework of the IRS, revealed a noticeable increase in incidents involving foreign material intrusion (FMI) in nuclear power plant systems. These incidents appeared to have safety impact, sometimes widespread, on many systems and components, including the reactor core, control rods, the secondary side, and other support systems such as the electrical, air and water systems.

More than ten countries contributed to the study by means of national information that is not part of the IRS database. Additionally, the World Association of Nuclear Operators (WANO) provided its analysis of the FMI problem, mainly from the point of view of human factor performance and maintenance activities.

The main recommendations of the study include:

- technical measures to avoid FMI (such as prevention measures, detection measures and design changes);
- human performance and procedural control (such as definition of foreign material exclusion (FME) zones, inclusion of the FME issue into the work planning process, training inspection practices in FME zones and reporting of FMI events).

5. STUDIES IN PROGRESS

There are two generic studies in progress: Requalification of safety-related equipment/systems following outages; and the IRS study of events.

The objective of the first study is to gain insights into the lessons learned by participating countries on the requalification process. Operating experience will be used in order to draw conclusions on practices. It has been observed that many requalification problems occur after maintenance and modifications.

The plan of work is to:

i) define the vocabulary[7];

ii) review and analyse relevant events;

iii) determine root causes (both technical aspects and human factor aspects);

iv) draw significant lessons learned.

Several combinations of searches have been tried thus far, and a number of events that exhibited weak operability verification efforts have been revealed. Corrective measures needed to cope with the identified problems are mostly procedural, meaning that procedures and work planning need to be improved or modernised. A lesser problem is in the organisation itself, or in the materials involved in the modification or requalification.

The second study, the IRS study of events which indicate non-compliance with operational limits and conditions (OL&C), involved in its first phase a review of IRS national co-ordinators' responses to a questionnaire on the topic and an analysis of both relevant IRS reports contained in the AIRS database and a selection of national events contributed by the members of the study group.

Various conclusions were drawn from these reviews and included the following:

- A significant number of OL&C non-compliances was caused by deficiencies in the manner in which operators translated OL&C requirements into other documents.
- It is important for the regulatory body and the operator to have a strong, common understanding as to what operability means.
- It is important for "surveillance" to be interpreted broadly, that is, to not only rely on surveillance tests, but instead to view other processes as components of the surveillance programme so that inoperable equipment may be detected promptly.

- Operators may benefit from categorising their own OL&C non-compliances to identify facility-specific trends and thus be able to develop more effective global corrective actions.
- It was found to be important that adequate functional tests be performed after maintenance to assure that equipment is restored to an operable status.
- It was considered important, where appropriate, to highlight OL&C values in procedures explicitly and to provide visual indications of OL&C on monitoring instrumentation.
- Operators take adherence to OL&C very seriously; however, competitive pressures (e.g. production pressures) may result in operators performing closer to limits which may result in an increased number of OL&C non-compliances in the future.

It is planned that the next phases of the study will perform the following activities:

- Initiate a detailed analysis of the questionnaire responses including a detailed analysis of the topics raised in the last question of the questionnaire (suggestions for further items to be included in the scope of the study).
- Determine if more detailed, system/function-based definitions of operability are appropriate.
- Assess the feasibility of creating a system or modifying the current IRS system to continue to trend these identified categories of OL&C non-compliances and disseminate the results to participating countries.
- Assess the implications of current activities in participating countries to remove items from the OL&C and relocate them to other documents so as to limit the OL&C to only the most important items.
- Conduct a further review of the draft safety guide planned as part of the IAEA Safety Standards Series entitled *Safety of Nuclear Power Plants: Operation, Operational Limits and Conditions and Operating Procedures*.

6. SPECIALIST MEETINGS AND WORKSHOPS

Specialist Meeting No. 1: Fuel and control rod issue[8]

At this specialist meeting on the fuel and control rod issue information was exchanged on, and lessons drawn from, operating experience, design evolution and safety aspects related to nuclear fuel and control rods.

The meeting was attended by 116 participants from a large number of countries, with a good balance between representatives from utilities, vendors and regulatory bodies. Technical sessions focused on operating experience and safety concerns; fuel performance and operational events; control rod issues; fuel design and fabrication improvements; and improvements in core management techniques.

Some conclusions reached include:

- There is a need for more testing, detailed analysis and regulatory oversight.
- Overall, fuel performance is satisfactory.
- Operational conditions are becoming more challenging, due to the length of the cycle and the extent of fuel burn-up.
- Fuel behaviour under these more demanding conditions is not always guaranteed, due to lack of a full experimental database.
- Some adverse affects include distortion of components, excessive formation of corrosion products and control rod interference.
- Possible causes of fuel assembly bowing (distortion) include excessive creep deformation; excessive compressive loads; grid influence; foreign material; long-term corrective action not fully defined on the basis of information available at this time.
- Lead test assemblies are useful, but not fully definitive as to behaviour.
- Fuel and control rod design will continue to evolve.

At the conclusion of the workshop, it was noted that there is a need for clear objectives for lead test assemblies; a need for more careful analysis of core management strategies; a need for enhanced oversight of fuel and control rod design changes; and a need for careful reviews of the assertion of the validity of a generic safety demonstration for a specific plant.

Specialist Meeting No. 2: Human performance in operational events[9]

A specialist meeting on human performance in operational events was held amongst NEA and IAEA specialists. This meeting was prompted by the concern that the human factor in operational events is recognised as an important contributor to plant risk, and that a more detailed study of this factor might reveal some areas where this risk factor might be reduced.

Some conclusions reached at this meeting include:

- Better human performance data are needed.
- A human factors analysis of root causes and corrective actions could reduce the frequency of significant events.
- For most reactors, little or no human intervention is desired or needed, with respect to actuation of safety systems.
- Modelling of human response is difficult and not yet mature for predicting the quantitative aspect of human performance, although progress is being made.
- There are common factors in human factors across industries (for example, civilian airplane events).
- Plant simulators play an important role in training, especially for abnormal events.
- Operator aids, such as computerised diagnostics, can assist the human response.
- Additional research in this area is indicated.

Specialist Meeting No. 3: Experience with thermal fatigue in LWR piping caused by mixing and stratification[10]

A specialist meeting on thermal fatigue was held in co-operation with the World Association of Nuclear Operators (WANO). The meeting was prompted by a number of piping cracks, including through-wall cracks, in safety and non-safety systems.

The discussion topics included operational experiences; thermal-hydraulic phenomena; material and structural response; monitoring aspects; inspection programmes; mitigation; prevention; and safety implications.

Some conclusions from the meeting were:

- Thermal fatigue is a recurring phenomena with low frequency affecting safety-related piping in a variety of safety systems.
- Better methods are needed to identify locations with potential risk.
- Temperature monitoring is an important part of the strategy to identify thermal fatigue locations.
- Changes in design and operating practices may be needed in some locations.

- Changes in non-destructive testing may be needed in some cases.
- Prevention of thermal fatigue is a multi-disciplinary task and calls for close co-operation between the designer, plant owner, and maintenance and operations staff.

7. CONCLUSIONS

Reactor safety is assured through conservative design criteria, construction and operation. One element of operational safety is the feedback of operational experiences. The Incident Reporting System (IRS) allows this feedback to take place on an international level by providing for the collection of events from a number of participating countries and by organising and disseminating this information in a user-friendly manner.

The objective of the IRS process is to enable timely reporting and feedback of events of safety significance on a world-wide basis. This process of sharing experience is carried out on a voluntary basis. In order to maintain the usefulness of the IRS, accurate and timely reporting by the national authorities is required.

Information about safety-significant events, and the subsequent lessons learned, is distributed to the countries that are currently operating nuclear power plants. This process, a vital part of operating experience feedback systems, has contributed to the following:

- New phenomena were detected.
- Safety information of a generic nature was distributed.
- Mistakes were corrected and the root causes and corrective actions were identified and circulated to the participating countries, thus contributing to operating reactor safety.

An additional aspect of this collective sharing of operational events is the expert review and analysis of events. This includes in-depth discussions on items of safety significance, generic studies, and various workshops and specialist meetings.

The several hundred reports received during this reporting period, the meetings where views were candidly exchanged and the generic studies undertaken should help ensure that lessons to be learned reach the authorities and utilities of the participating countries. Feedback from the IRS provides a necessary ingredient of operational safety.

NOTES

1. Thermal fatigue was discussed extensively at a specialist meeting sponsored by the NEA in June 1998, as reported in NEA/CSNI/R(98)8.

2. During this reporting period there was a specialist meeting on Human Performance in Operational Events. The proceedings were published as NEA/CSNI/R(98)16.

3. See *Latent Failures of Safety Systems*, NEA/CSNI/R(97)5.

4. See *Operating and Maintenance Experience with Computer-Based Systems in NPPs*, NEA/CSNI/R(97)23.

5. See *Role of Simulators in Operator Training*, NEA/CSNI/R(97)13.

6. See *Foreign Material Intrusion in Plant Systems*, IAEA-J4-CS-58/98.

7. It was observed that requalification is not a keyword in the IRS database, so practices and definitions must be clarified as part of the study.

8. See *Proceedings of the Specialist Meeting on Nuclear Fuel and Control Rods, Design Evolution and Safety Aspects*, NEA/CSNI/R(97)2.

9. See *Human Performance in Operational Events: Proceedings*, NEA/CSNI/R(98)16.

10. See *Experience with Thermal Fatigue in LWR Piping Caused by Mixing and Stratification*, NEA/CSNI/R(98)8.

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