IAEA TECDOC SERIES

IAEA-TECDOC-1762/Rev. 1

IAEA-TECDOC-1762/Rev. 1

Operating Experience from Events Reported to the IAEA Incident Reporting System for Research Reactors

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IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

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OPERATING EXPERIENCE FROM EVENTS REPORTED TO THE IAEA INCIDENT REPORTING SYSTEM FOR RESEARCH REACTORS

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

For further information on this publication, please contact:

Research Reactor Safety Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

Operating experience feedback is an effective mechanism in providing lessons learned from events and the associated corrective actions to prevent them, resulting in improved safety at nuclear installations.

The Incident Reporting System for Research Reactors (IRSSR), operated by the IAEA, is an important tool for exchanging research reactor operating experience feedback between Member States. The IRSRR reports contain information on events of safety significance with their root causes and lessons learned, which helps reduce the number of similar events occurring at research reactors. To improve the effectiveness of the system, it is essential that national organizations take appropriate steps to report events important to safety in a timely manner and share the information in the IRSRR database.

At their biennial technical meetings, the national coordinators of the IRSRR suggested collecting and disseminating the operating experience feedback from the events reported to the IRSRR in an IAEA publication.

IAEA-TECDOC-1762, Operating Experience from Events Reported to the IAEA Incident Reporting System for Research Reactors, published in 2015, provides a summary of operating experience feedback from the events reported to the IRSRR up to September 2014 based on the root causes, safety significance, lessons learned, corrective actions and causal factors. The present updated and revised publication, IAEA-TECDOC-1762/Rev. 1, includes the operating experience feedback from events reported up to May 2022. The publication also contains relevant summary information on research reactor events from sources other than IRSRR, operating experience feedback from the International Reporting System for Operating Experience considered relevant to research reactors, and a description of the elements of an operating experience programme as established by the IAEA safety standards.

The intended audience of this publication is research reactor operating organizations, regulatory bodies, designers and any other organizations or individuals involved in the safety of research reactors.

The IAEA wishes to thank the contributors to this publication for their efforts and valuable assistance. The IAEA officers responsible for this publication were N. Laine, F. Naseer and A. Shokr of the Division of Nuclear Installation Safety.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Since 1997, the IAEA has operated the Incident Reporting System for Research Reactors (IRSRR). The information on the safety significant events occurring in research reactors is submitted to the IRSRR by the national coordinators in accordance with the IRSRR guidelines [1]. The event reports are discussed in the regular meetings of the IRSRR national coordinators and included in the system database, to which secured access is provided to the Member States participating in the system.

The importance of an effective use of operating experience feedback in enhancing the safety of nuclear installations is well recognized. The INSAG-23 report, Improving the International System for Operating Experience Feedback [2], has recommended that operating experience feedback systems should not be limited to reporting events, but also consider all factors that could affect or aid in enhancing safety.

Event reporting needs to be connected to programmes that transform the lessons learned into actions such as improvements in management of reactor operations and ageing, training, design, and operating programmes and safety culture. An effective operating experience feedback programme facilitates the sharing of experiences leading to corrective actions being taken following safety significant events. In 2018, IAEA Safety Standards Series No. SSG-50, Operating Experience Feedback for Nuclear Installations [3], was published to provide guidance to Member States on establishing an operating experience feedback programme in their installations.

During the biennial meetings, the IRSRR national coordinators recommended collecting and disseminating, via an IAEA publication, the operating experience from the events reported to the IRSRR.

1.2. OBJECTIVE

The objective of this publication is to provide the updated operating experience feedback from the events reported to the IRSRR, including safety significance, root cause(s), lessons learned, and corrective actions taken to prevent the occurrence of similar events in other reactors. The publication is intended for use by research reactor operating organizations, regulatory bodies, and designers.

1.3. SCOPE

The publication covers the analysis of the reported events to the IRSRR up until May 2022, with a focus on their root causes, safety significance and lessons learned. The publication also provides the key lessons learned from the recent events in nuclear power plants (NPPs) that are relevant to research reactors. Reference to other publications that cover research reactor events is also included. An outline of an operating experience programme is provided, which could be useful for developing an operating experience programme at research reactors [3].

1.4. STRUCTURE

Section 2 of this publication describes the IRSRR with its key features. Section 3 provides an overview of the events reported to the IRSRR. Section 4 discusses the events reported to the IRSRR, including root causes, safety significance, lessons learned, and corrective actions established on the basis of these events. Section 5 provides brief conclusions. The annexes provide references to other relevant publications, lessons learned from recent events at NPPs that are relevant to research reactors, and a description of the main elements of an operating experience programme in accordance with the IAEA safety standards.

2. THE INCIDENT REPORTING SYSTEM FOR RESEARCH REACTORS

2.1. WHAT IS THE IRSRR?

Systematic collection and evaluation of operating experience from unusual events is an effective way of improving operational safety. The IAEA operates and maintains, within its programme on research reactor safety, an Incident Reporting System for Research Reactors (IRSRR). The IRSRR collects, maintains and disseminates reports on events which are received from IAEA Member States participating in the system. Some of the events reported to the IRSRR are also rated in the International Nuclear and Radiological Event Scale (INES; see Section 2.4.3 for further details).

The IRSRR was established in 1997 for the purpose of facilitating the exchange of information between research reactor facilities and sharing the causes and the lessons learned from these events, in order to avoid the reoccurrence of similar events in other facilities. The IRSRR is a web-based system on the NUCLEUS portal of the IAEA. Access to the IRSRR database is restricted to the nominated national and local coordinators.

Requirements on incident assessment and reporting, as well as on the use of operating experience, are included in IAEA Safety Standards SSR-3, Safety of Research Reactors [4], which states in para. 7.9:

“It shall be the responsibility of the operating organization to ensure the following: …

(k) Information on events with safety significance that are required to be reported to the regulatory body, including any assessments of such events and the corrective actions intended, is submitted to the regulatory body.

(q) Operating experience, including information on operating experience at similar research reactors, is carefully examined for any precursor signs of tendencies adverse to safety so that corrective actions can be taken before serious adverse conditions arise and recurrences can be prevented.”

The Code of Conduct on the Safety of Research Reactors [5] states that “the regulations and guidance established by the State or the regulatory body according to national arrangements should require the operating organization to report the occurrence of events significant to safety in accordance with criteria established by the regulatory body” (para. 20 (b)), and that “the operating organization should report events significant to safety to the regulatory body, analyse the events and act upon the findings to improve safety in a timely manner" (para. 32 (e)).

2.2. BENEFITS OF THE IRSRR

As a platform for sharing the operating experience of research reactors worldwide, the overall benefit of the IRSRR is in the safety improvement of research reactors. The participating Member States benefit through the exchange of information on the events, the lessons learned, and corrective actions taken by the operating organization. This heightens the awareness among the participating Member States to take proactive actions for preventing similar events in their research reactors.

The IRSRR may also be used for identifying trends and safety deficiencies of a generic nature. The analysis of events helps in identifying and implementing measures to mitigate the consequences of the events.

Another use of the IRSRR data is the application of operating experience feedback in the design of new research reactors.

The IRSRR is a global contact network and forum that enables the research reactor community to share and review information on lessons learned from reported events. The system can be used to obtain information on various issues having safety significance and to assist in the prioritization of the areas where further resources or research may be directed.

2.3. HOW DOES THE IRSRR WORK?

2.3.1. Event reports

Each participating country designates a national coordinator who is responsible for event reporting to the IRSRR. Reporting the event to the IRSRR is voluntary. Guidelines and user manuals are available to the users of the IRSRR. Events that meet one or more of the following criteria could be considered as appropriate for reporting to the IRSRR:

- The unusual event identifies important lessons learned that allow the international research reactor community to prevent a recurrence of a similar event or to avoid the occurrence of a more serious unusual event in terms of safety; or
- The unusual event is itself (potentially) important or serious in terms of its safety implications or whether it (potentially) reduces the defence in depth significantly; or
- The unusual event is a repetition of similar events previously reported to the IRSRR, but identifies new lessons learned.

The report can be submitted as preliminary, which can contain the known details at the time of reporting. Subsequently, a main report, replacing the preliminary report, is prepared and submitted. If additional information becomes available at a later stage, a follow-up report may be generated and submitted.

The report contains the title and the date of the event, an abstract, a narrative description of the event, a preliminary safety assessment (what were the direct causes, consequences and implications), a root cause analysis, corrective actions, and lessons learned. The written report is often supported by drawings, photos and sketches. The national coordinator also identifies the categorization codes for the important aspects of the event in accordance with the coded watchlist of the IRSRR guide and assigns the report as 'specific report' or 'generic report'.

2.3.2. Sharing information

The IRSRR is a part of the web-based common platform for incident reporting of the IAEA NUCLEUS portal (see Fig. 1). The system allows access only to the authorized coordinators of the Member States. The user manual comprises detailed information on the use of the system. Once a new report is posted on the IRSRR, the registered users are informed by email and can view the reports.

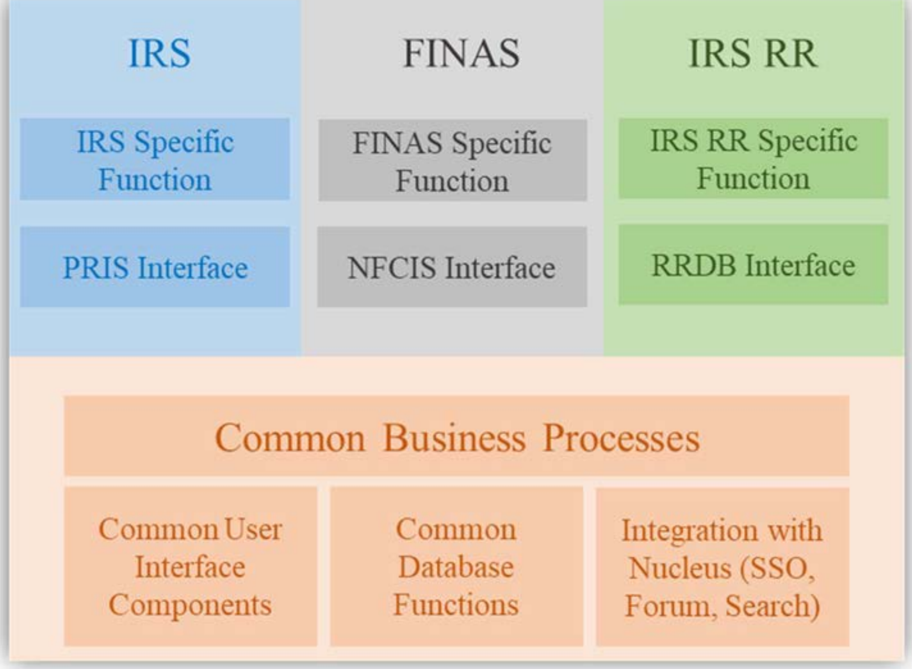

FIG. 1. IAEA's incident reporting systems for nuclear installations.

2.4. HOW IS THE IRSRR USED?

2.4.1. Meeting of national coordinators

A biennial meeting of national coordinators is held with the purpose of exchanging information on reported events. The participants also discuss ways to improve the functioning of the IRSRR. These meetings serve to strengthen the mechanisms for the exchange of experience in the assessment of events and in improvements made to reduce the frequency of similar events. Experts also provide training to the participants on event investigation techniques.

2.4.2. Restricted access

Access to the IRSRR reports is restricted and is limited to the authorized coordinators of the participating Member States. This restriction encourages openness among the participating Member States to disclose the event details. The main purpose of the system is to facilitate the benefits of the exchange of the experience among the participating Member States.

2.4.3. Communication through INES

The IAEA and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA) jointly operate and maintain the INES. INES was introduced in 1990 and its primary purpose is to facilitate communications and understanding between the nuclear community, the media and the public on the safety significance of nuclear and radiological events occurring at nuclear installations. INES is not a notification or reporting system, and it should not be used in emergency response. It is expected that relevant events at research reactors communicated through INES are also reported to the IRSRR.

2.5. WHAT HAS BEEN ACHIEVED?

Up until April 2023, 61 Member States with an interest in research reactors have been participating in the IRSRR (see Table 1). As of May 2022, there have been 238 event reports from 45 Member States in the IRSRR database. The oldest report is from an event that occurred in 1945 and the most recent being from 2021. In order to maximize the benefits from IRSRR, it is necessary that the participating Member States submit the events that have an element of lessons to be learned, including precursors to events.

Over the years, IRSRR has developed from a source of information exchange on events to becoming a source for analysis, detailed discussion on the events, refining the event investigation techniques and the IAEA meetings for the exchange of information related to operating experience [6]. The analysis of the events is also used to determine generic and common causes for the events and serves as important feedback for consideration when identifying the topical areas for planning IAEA activities on research reactor safety. As of 2022, 12 biennial technical meetings of the IRSRR national coordinators have been held.

TABLE 1. MEMBER STATES PARTICIPATING IN THE IRSRR AS OF APRIL 2023

Algeria
Argentina
Australia
Austria
Bangladesh
Belgium
Bolivia
Brazil
Bulgaria
Canada
Chile
China
Colombia
Czech Republic
DR of Congo
Egypt
Finland
France
Germany
Ghana
Greece
Hungary
India
Indonesia
Iran
Iraq
Israel
Italy
Jamaica
Japan
Jordan
Kazakhstan
Korea, Republic of
Latvia
Libya
Malaysia
Mexico
Morocco
Netherlands
Nigeria
Norway
Pakistan
Peru
Philippines
Poland
Portugal
Romania
Russian Federation
Saudi Arabia
Serbia
Slovenia
South Africa
Sudan
Syria
Thailand
Tunisia
Türkiye
Ukraine
United Kingdom
United States of America
Uzbekistan
Viet Nam

3. OVERVIEW OF THE EVENTS REPORTED TO THE IRSRR

The events reported to the IRSRR are characterized using a set of guide words as defined in Appendix II of the IRSRR guidelines [1]. There are nine groups of guide words in the IRSRR guide, as follows:

- Reporting categories;
- Reactor status prior to the event;
- Failed/affected systems;
- Failed/affected components;
- Cause of the event;
- Effects on operation;
- Characteristics of the incident;
- Nature of failure or error;
- Nature of recovery actions.

Within each group mentioned above, the set of guide words are assigned numerical codes. The guide words describe the typical systems, root causes, consequences, affected systems and/or components, etc., which generally characterize research reactor events. The national coordinators select the applicable guide words on the web-system when entering an event report. It is noted that more than one guide word can be selected within each group. The IRSRR guide words are a simplified means to search and retrieve the information on events. The events reported to the IRSRR were analysed with the help of these guide words and an overview of the analyses is presented below.

a) The reporting category of an event identifies the category into which an event falls in accordance with the IRSRR guidelines. It is noted that an event may fall into more than one reporting category and, hence, some overlap is unavoidable.

   Among the events analysed, the largest number of events (47%) were reported in the reporting category of ‘deficiencies in design, construction, operation (including maintenance and periodic testing), quality assurance or safety evaluation, including experimental devices and isotope production facilities’, followed by ‘degradation of barriers and safety related systems (including experimental devices and isotope production facilities important to safety)’ (25%). About 15% of the events were reported in the category of ‘unanticipated releases of radioactive material or exposure to radiation’, 11% of the events were reported in the category of ‘potential safety significance (potential unsafe situation)’, and 2% of the events were reported in other categories, which includes ‘generic problems of safety interest’, and ‘effects of unusual external or internal events’. Figure 2 shows the distribution of events based on the reporting category.

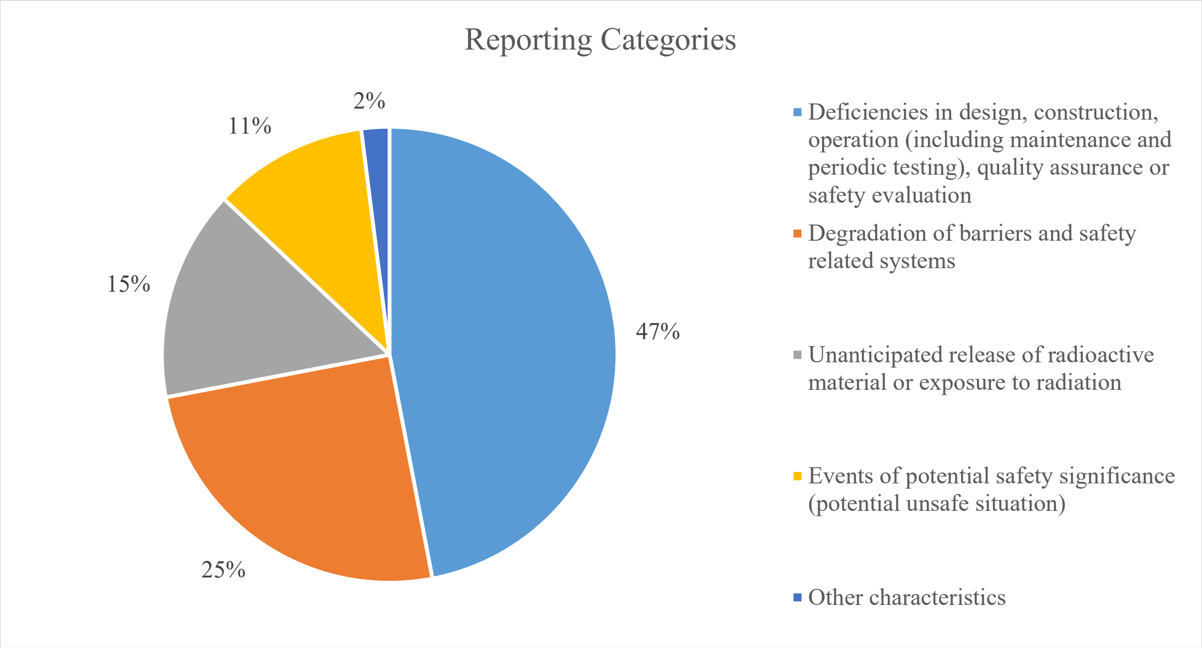

FIG. 2. Distribution of the analysed events among reporting categories.

b) The analysis of the event reports showed the following grouping according to the characteristic of events: The largest number of events resulted in 'degradation of the reactor coolant boundary' (18%), followed by failure or degradation of reactivity or reactor control (14%), 'other characteristics', which include events related to radioactive waste, loss of electrical power, and external hazards (14%), degradation or malfunctioning of experimental device (13%), loss or significant degradation of safety function, which includes degradation of reactor containment or confinement, and failure or significant degradation of heat removal capability (13%), fuel handling and degraded fuel (12%), 'transient', which includes reactor power, pressure, or temperature transients (9%), and finally, 'discovery of a major condition not previously considered or analysed' (7%). Figure 3 shows the distribution based on the characteristics of the events.

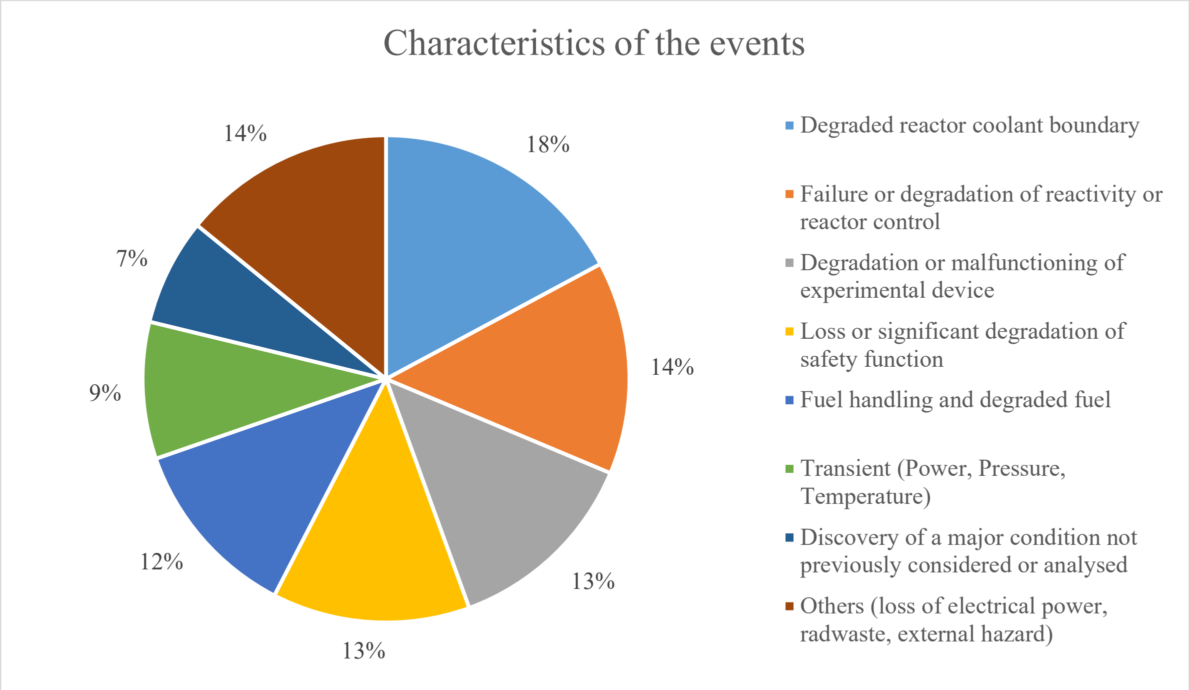

FIG. 3. Distribution of the analysed events based on the characteristics of the event.

c) The analysis of the events showed that mechanical components (63%) were the most affected components of research reactors, followed by instrumentation (gauges, transmitters, sensors, and computers) (20%) and electrical components (14%). In (3%) of events, no specific component was involved. Figure 4 shows the distribution of failed or affected components.

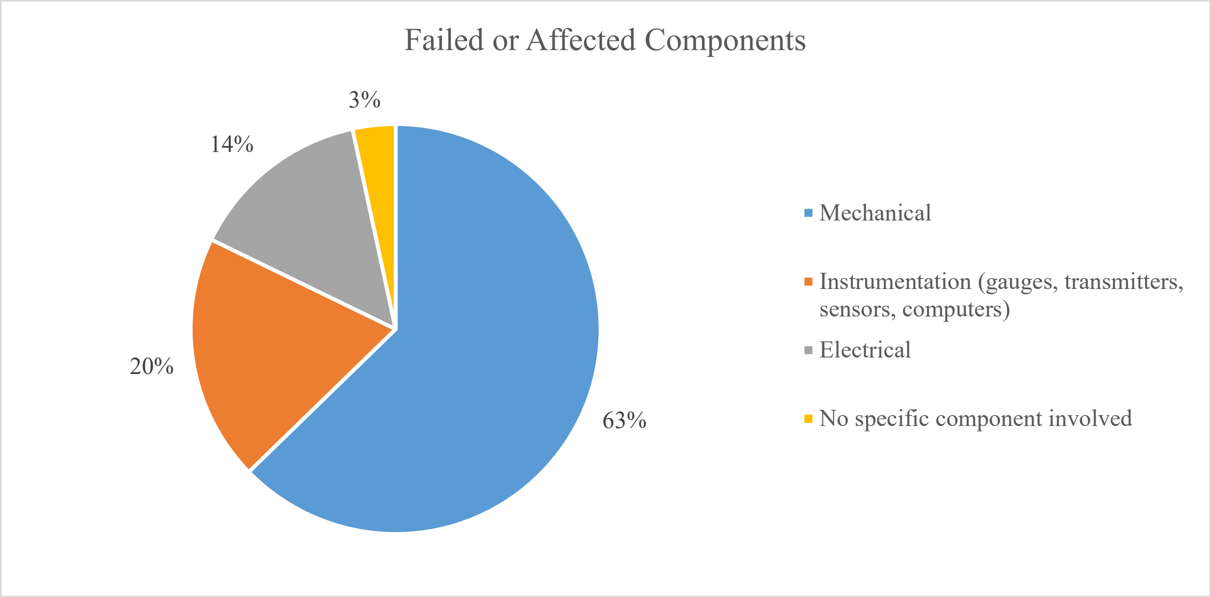

FIG. 4. Distribution of the analysed events among failed or affected components.

d) The analysis of the causes of events showed that the leading root causes of events were ‘human factors’, including inadequate or ineffective use of procedures, inadequate training, and errors of omission and commission (37%), and ‘ageing of structures, systems and components (SSCs) due to corrosion, fatigue, crack, vibrations, and obsolescence, or deficiencies in maintenance’ (36%). Other important contributors were related to deficiencies in ‘management of safety’ including lack of safety culture and inadequate management system (14%), and inadequate ‘design and quality assurance’, including control of modifications and utilization projects (12%). Figure 5 shows the distribution of root causes for the analysed events.

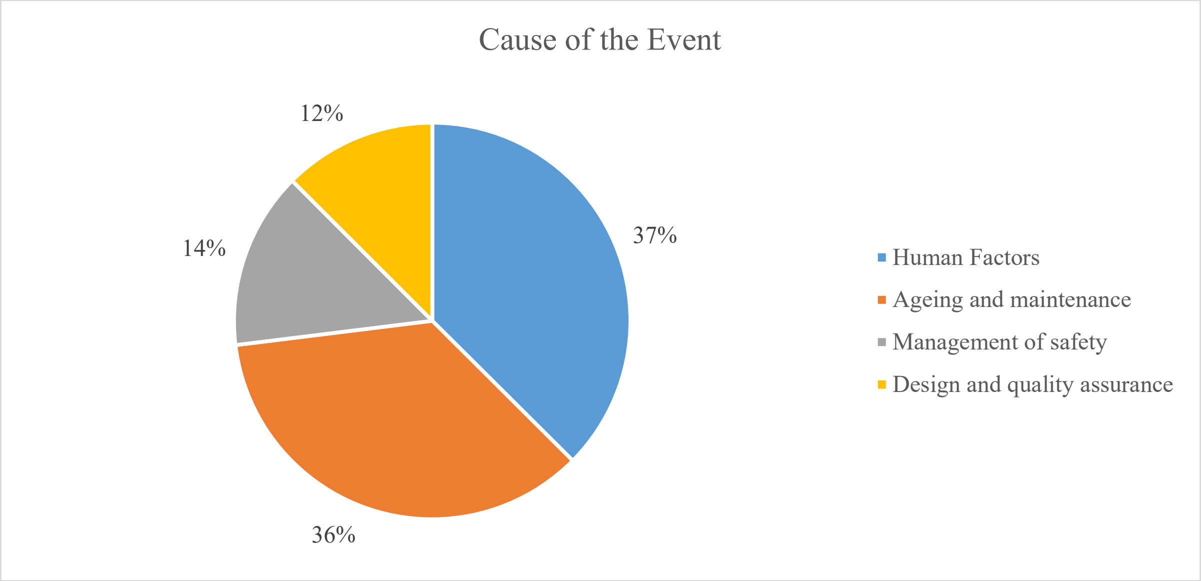

FIG. 5. Distribution of the analysed events based on the cause of events.

4. EXPERIENCES WITH THE IRSRR

The events reported to the IRSRR database have been grouped into topical subject fields based on the issues presented in the reports. In most cases, the event grouping was self-evident from the incident report, while in some cases it was deduced from the available information in the reports.

Event investigation tools and techniques such as cause and effect analysis, task analysis, change analysis, and barrier analysis were used for analysis of the events to arrive at the root cause(s) of the reported events. Further information on event investigation methods is available in Ref. [7].

It is also noted that there are many events that have been presented at past IRSRR meetings and in other publications, which have not been submitted to the IRSRR database. This deficit has been minimized to some extent by the discussion of events from other sources in Annex 1.

With respect to human factors, it is understood that many events have some aspect of human factors associated with them if assessed through levels of causality down to the root cause: be it by omission in design, lack of quality control, or the failure to provide training or managerial oversight. In order to preserve the nature of the subject groupings, the analysis is therefore focused on the direct causes. This also applies to the events discussed in the section on human factors, where it is clear from the report that the contribution by humans to the event is a direct or marginally indirect cause.

It is important to note that, during the earlier years, more events were reported due to design deficiencies and inadvertent criticalities, often resulting in serious consequences. The analysis of the events reported to the IRSRR shows that, over the years, these shortcomings have been overcome and the events due to these causes have been significantly reduced. In more recent years, human factors and ageing have dominated the cause of the events. With most of the research reactors being operating for more than 40 years, ageing management of these reactors is an increasing concern. Human factors, however, continue to contribute to a large number of events and remain an issue.

4.1. EXPERIENCE WITH DESIGN, INSTALLATION AND COMMISSIONING

4.1.1. Summary of the root causes

A significant number of events reported to the IRSRR were caused by deficiencies in design, installation and commissioning. These deficiencies are closely linked to shortfalls in the quality assurance control systems affecting not only the design, installation and commissioning stages of the research reactors themselves, but also the design, installation and commissioning process of various modifications introduced throughout the lifetime of the reactor [8].

The following Sections 4.1.1.1 to 4.1.1.5 describe deficiencies associated with specific areas.

4.1.1.1. Control rods

Several events related to the design of control rods were reported to the IRSRR during the last two decades. Many of these operating experiences involved rods that were stuck due to design deficiencies. In one case, a control rod (modified design from oval to fork type control blade) failed to insert into the core. The following investigation and visual inspections identified that the control rod was stuck to a control fuel element and while withdrawing the control rod, the control fuel element was also withdrawn from the core. The control rod design (insufficient tolerances) and inappropriate quality control during the manufacturing process were identified to be the root causes. Moreover, an inadequate use of operating experiences at the same facility caused a similar event to recur two years later.

Another report indicated that absence of technical specifications for manufacturing tolerances of the control rod components, in conjunction with inadequate quality assurance, caused a control rod to become stuck in the fuel cell. The design deficiency was found to have existed since the system was commissioned.

One event report described that an unexpected ^{60}Co activity was detected in the primary cooling circuit. Inspection and analysis excluded the possibility of damaged fuel elements. The investigation identified that the radioisotope originated as an impurity of the control rod nickel coating. The root cause was identified to be the poor selection of the rod coating.

4.1.1.2. Selection of materials

Some of the events in this category occurred in the 1950s and 1960s. In one event, pieces of the seal gasket (tetralin – an organic compound having the chemical formula $C_{10}H_{12}$) of the primary pump found its way into the primary cooling system and subsequently decomposed under irradiation; the decomposed products coated the fuel elements and blocked the cooling channels of many of the fuel assemblies. The inadequate heat removal resulted in the partial melting of fuel with the subsequent release of fission products into the primary cooling circuit. The inappropriate gasket material was identified as the root cause of the event. In another event, lead was used to manufacture components located in a high neutron field. This design oversight led to radiation induced swelling of the lead components which caused subsequent difficulties during the removal phase of the affected components and their counterparts.

Two events identified that debris of inappropriate material used in the cooling water circuit caused water flow blockages. One of these events occurred in the 1970s in which the inner surface rubber liner of the primary coolant hold-up tank became separated from the tank. Pieces of the rubber liner blocked the primary circuit pump inlet and caused a flow reduction. The other event from the 1990s reported a blockage of the continuous sampling circuit due to debris of plastic lining of the primary cooling circuit.

Another report identified the cause of siphoning of the pool water to be the use of plastic pipes that were damaged. Another event occurred when a polyvinylchloride pipe was selected for the pipework of the pool water demineralizer; the damage to the pipework resulted in a partial drainage of the reactor pool.

4.1.1.3. Nuclear fuel

One event was raised when during a routine inspection of the core, a fuel plate was found to be dislodged from its original position in the fuel assembly. The investigation showed that the fuel assembly design and implementation of fuel assembly manufacturing process was inadequate. The roll swaging process that clamps the fuel plates into side plates did not provide sufficient joint strength to prevent longitudinal plate movement. Furthermore, the fuel lacked a design feature that would limit or prevent this movement. An additional contributory factor was identified to be the inadequate review of the fuel design change and manufacturing process.

Another event occurred in the 1990s in which the poor design of the joint between the fuel cladding and thermocouple of an instrumented fuel assembly led to the joint failure and subsequent release of fission products into the pool water during the fuel irradiation.

An event dated in the 1960s reported a faulty fuel assembly cladding that separated from the fuel plate. The cladding partially blocked the cooling channel causing fuel overheating which in turn resulted in fuel failure and the release of radioactive material into the pool water.

Another event resulted in reactor power being downgraded due to inadequate thermal hydraulic performance following core reconstruction. Fuel assemblies experienced excessive vibrations after the core was reconstructed with new fuel assemblies. Detailed investigations showed that vibrations were related to the fuel temperature, but the root cause could not be conclusively established. Modifications to the top grid plate and fuel end fittings were carried out to improve thermal hydraulic performance, and reactor power was limited to less than design power to limit the coolant temperature.

In a recent event, a reactor which was operating at 50% power after a refuelling process, automatically shut down due to a high reading at the reactor stack monitor. Following shutdown, the reactor operating personnel conducted environmental sampling at the confinement building exhaust stack and at the designated emergency site boundary locations. Sample results indicated that radioactive material of a small fraction of the release limits established by the regulatory body was released. Follow-on investigation indicated that a fuel element was not securely in place in its position in the reactor core grid, preventing adequate coolant flow to the fuel element.

The reported fuel failures were generally detected by a rise in the activity levels of the primary coolant and, in some cases, by a rise in the activity levels in the stack discharge. In some of the cases, the cause of the failures could not be conclusively established. In one case, the fuel was damaged during handling, but it could not be determined how. In another case, an apparent temperature rise in an instrumented fuel assembly was reported, although inspection and analysis did not confirm any temperature rise.

4.1.1.4. Primary cooling system components

Some events were associated with design shortcomings of components of the primary cooling system. In one case, several modifications to the primary system were implemented to increase the reactor power, which also affected the pressure profile in the primary cooling circuit. After the reactor was restarted, air bubbles were observed in the reactor pool during the primary cooling pump operation. The investigation identified that, due to the pressure changes in the circuit introduced during the power upgrade, the upper section of a vent pipeline broke resulting in air ingress. The wall thickness of the vent pipe had reduced due to corrosion over the past reactor operation to such an extent that the primary circuit pressure changes were sufficient to cause the pipe break. In addition to other lessons, this event also highlighted the importance of adequate assessment of the effect of a modification on the rest of the reactor facilities.

Another report identified an inappropriate design of the delay tank as the root cause of the event. The plant designers located the tank in an upper section of the primary cooling circuit vertically close to the siphon breaker and reactor pool surface. This configuration resulted in gas accumulating in the tank during the reactor operation. When the reactor was in a shutdown state, a large amount of gas was released into the reactor pool. These changes also caused the reactor pool water level to fluctuate during the operation depending on the amount of water that is displaced by the gas pocket in the tank. To resolve the issue, an extraction line was designed to provide continuous de-aeration of the tank.

In one event, it was found that a malfunction of a primary cooling circuit flap valve caused a leak of the primary coolant into the reactor pool. The water jet caused a disturbance of the hot water layer in the pool that resulted in an increased radiation level at the pool top. This internal leak also caused a minor core flow bypass. The event investigation identified that the design deficiency of the flap valve and its gasket were the root causes.

A leak caused by the corrosion of the primary coolant pipe weld was reported. The pipe weld was located behind the shielding and, therefore, was not easily accessible or inspectable.

A primary coolant leak that originated from a defect in the pool liner was reported. The water from the defect in the liner accumulated in the interspace between the liner and the concrete construction work and eventually collected. At the time of construction of the reactor, this interspace was filled with coal tar for insulation, which, due to a design or a material fabrication flaw, never solidified entirely. The water, that had accumulated in the interspace from the leakage due to the defect in the pool liner, created flow paths in this unsolidified material and advanced the corrosion of the aluminium pool liner.

4.1.1.5. Other components

One event reported a laboratory fire caused by the failure of a dryer in a hot cell facility containing radioactive waste. The fire was contained and extinguished without undue release of radioactive material into the environment, but the combustible materials (paper and textiles) inside the hot cell facility were destroyed, and the hot cell facility was contaminated. The investigation revealed that the dryer was not designed for this application, the technical specifications of the equipment for maintenance and testing were absent, and the working procedures were found to be inadequate as well as irrelevant.

In one event, ^{137}Cs activity was detected in the spent fuel storage pool. Spent fuel was stored in either a secondary aluminium barrel or a stainless-steel container. The cause of the event was determined to be the lack of chemistry control of the pool water, as no provision was made in the design of the spent fuel storage pool water system, and the improper design of secondary containers (not leak tight) led to the corrosion of both the secondary container and the fuel clad.

A pneumatic transfer system which contained a pipe joint between an aluminium pipe and a plastic pipe in the reactor pool was being tested with air pressure, when the joint failed and pool water siphoning started. Alertness of the personnel who removed the upper plastic pipe from the pool stopped further siphoning. The event shows the design weakness of using a joint in an inaccessible location, the failure of which can lead to serious consequences.

In one event, an inadequately designed preamplifier in the automatic power regulation circuit failed in certain operating conditions (high neutron flux coupled with high neutron flux rate), saturating a capacitor, thereby causing reactor power to increase as the control system detected reactor power to be lower than set power, resulting in the withdrawal of the control rod.

In another event, an instrumented fuel assembly failed and released radioactivity into the coolant. The event showed design deficiency and inadequate quality of components in the power regulation system. The consequences were minimal as the reactor was being operated at lower than the rated design power and xenon poison build up at the time of the event, which limited the insertion of excess reactivity.

Another event was an accidental flooding of neutron measurement channels during the transfer of water from spent fuel storage to the reactor pool. These normally dry channels contained the ionization chambers for neutron flux measurement, and the resulting erroneous flux measurements caused an automatic reactor scram. Flooding of the channels took place earlier during pumping of water from the spent fuel storage pool to the reactor pool. No protective devices were provided on the channels containing ionization chambers to prevent their flooding. In addition to this design deficiency, the lack of an approved operating procedure for pumping water from the spent fuel storage pool to reactor pool was identified as the contributory cause.

A safety valve in a hot neutron source facility — installed in a double containment to prevent over pressurization of the inner containment — was found to be opening at a lower differential pressure during commissioning. The investigations showed that the valve was calibrated under different discharge pressure conditions than the actual operating conditions, and this caused the valve to open prematurely. The event highlights the need to calibrate the safety valves suitable to operating conditions.

During shim rod testing, a shim rod failed to move in, and the reactor was scrammed manually. The cause was identified to be a failed switch that was preventing power from being supplied to the shim rod drive. The investigation revealed that switch failure occurred in other switches of the same brand, indicating the possibility of a design flaw.

A fire in the uninterruptible power supply unit of the reactor control and monitoring system rendered the system unavailable and the reactor was scrammed automatically. The investigation revealed that the possible cause of the fire could be from the rectifier capacitor operating in a higher temperature range than anticipated.

In another event, the microcomputer close loop system that monitors the reactor parameters, except the dose rate, went into hibernation, thus losing reactor parameter monitoring. The cause of the event was identified to be long idling, where the computer system was not refreshed. A practice of refreshing the system at a fixed interval was introduced.

An underwater light broke in the reactor pool due to water seeping into the lightbulb due to improper installation, with the glass fragments dropping into the reactor pool. The investigation of the event resulted in corrective actions to include adoption of underwater lights with higher efficiency sealing and installing mesh screens around the lights to prevent distribution of glass fragments in the reactor pool in a similar occurrence.

A research reactor building was flooded with water from the fire protection system due to inadvertent opening of the deluge valve as a result of design deficiencies in the logic system. The power to the facility was shut off for maintenance work causing the fire water jockey pump to remain in a shutdown state. A temperature sensor that opens the deluge valve sent the signal for the deluge valve to open due to power not being available to the sensor. The situation led to both the deluge valve and the manual valve remaining open when power was off. When the power supply was restored, the jockey pump started, and water flowed through the deluge valve, flooding the reactor building.

4.1.2. Safety significance

The reported event related to an inadequate fuel assembly design where its fuel plates moved longitudinally, could have resulted in inadvertent reactivity control issues, probable damage of fuel plates, and subsequent release of fission products.

The report describing the issue of gas accumulation in the decay tank during the reactor operation resulted in the spillage of contaminated pool water. Moreover, the gas trapped in the delay tank could have contained activated and fission product radioisotopes. Once the gas was released, the personnel working at the pool top could have been exposed to unnecessary radiation dose.

The event of modified control rods has several safety aspects. An inadequate management system (with respect to design review and quality assurance) resulted in the acceptance of inadequate design, thereby causing unsafe failure of control rods. Sudden release and dropping of a stuck control fuel element could have caused serious consequences.

Issues associated with the design of control rods could have resulted in a common cause failure, affecting multiple control rods. Such a situation could have caused more severe consequences, such as an uncontrolled increase in reactor power.

Events such as flooding of ionization chambers or failure of the signal processing components that result in lower than actual signals detected by the reactor control system can have potentially severe consequences, since automatic power control systems tend to increase reactor power. The consequences can be limited by other factors, such as the amount of excess reactivity present in the reactor, negative temperature coefficients, and other redundant and independent safety provisions like trips on high temperatures and/or high radiations.

The use of equipment (dryer) not designed for the application could have resulted in an inadvertent release of radioactive material. In the case discussed above, the risk was low; however, it indicated the importance of conducting the appropriate risk assessment of processes and design modifications prior to commissioning and operation.

The deficiencies in design of secondary containers for spent fuel assemblies as well as inadequate design of the spent fuel pool, particularly the lack of a continuous water purification system, caused a release of fission products into the pool water. This design oversight caused an increase in the risk of personnel contamination, radiation exposure, and the release of radioactive material into the environment.

Deficient operating procedures, insufficient training of operating personnel, and inadequate managerial oversight of the reactor core refuelling process led to the improper placement of a fuel element in its core grid position after refuelling caused fuel failure, releasing fission products into the primary coolant, contaminating components of the primary cooling system, and releasing radioactivity into the environment.

Deficiencies in the design and construction of a reactor cooling system may aggravate with time during operation, giving rise to long term consequences, including loss of coolant. Leaks from the pool liner could also damage the concrete by corroding the reinforcement.

The unavailability of the monitoring systems could have adverse effects on safety. In the absence of sufficient information, the operator may not be able to monitor facility parameters to take corrective action if a fault develops.

Foreign material in the primary coolant system has several possible safety implications, such as blockage of flow, generation of activation products, wear and scratch of other components including fuel.

Spurious actuation of the fire protection system and subsequent flooding may damage SSCs important to safety, rendering them unavailable when they are needed.

4.1.3. Lessons learned

The following lessons are learned from the events reported in this category:

- The design and modification projects have to be subjected to an appropriate review and approval process, and take into consideration ageing of the structures, systems or components involved [9];
- The design has to consider the possibility of inadvertent increase in reactor power due to failure of components in the reactor control system;
- Thermal-hydraulic design of the reactor core has to be thoroughly reviewed before making any changes in the core design [10];
- The effect of radiation has to be considered in the design of components and the selection of materials for use in the radiation field;
- Long term storage of fuel elements in storage pools requires special attention with respect to maintaining the integrity of the fuel cladding and the secondary containers through proper water chemistry monitoring and control, and design of containers, to prevent failures and release of activity into the pool water;
- Adherence to an effective quality assurance system that includes manufacturing, storage, and handling of fresh fuel could reduce fuel failure events. Additionally, it is important that fuel failures are detected early, to remove the failed fuel and limit the extent of radiological hazards.
- Adequacy of operating procedures, including clear description of step-by-step instructions and adherence to them, as well as appropriate quality checks and verifications, sufficient training of operating personnel on the use of proper fuel handling tools, and effective managerial oversight of the refuelling process are essential for ensuring operational safety of the reactor.
- Design and construction activities have to follow an effective quality assurance programme to prevent defects which are difficult to be corrected later, such as pool liner flaws or defects in inaccessible SSCs locations.
- The design has to take into account the failure of components especially in the reactor control and protection systems and any unsafe situation arising due to such failures. Suitable provisions have to be made to preclude unsafe situations.
- It is important to ensure that the fire protection system is designed such that spurious actuation and subsequent flooding is prevented.

4.2. EXPERIENCE WITH QUALITY ASSURANCE PROGRAMMES

4.2.1. Summary of the root causes

The weaknesses of quality assurance programmes, especially inadequate or the absence of quality control, were major contributors to many events. Some of them are discussed below.

Five events reported failure of fuel element cladding between the early 1980s and late 1990s. In all cases, increasing radioactivity levels of the primary coolant were identified after short operation periods and the reactors were shutdown. Failed fuel elements were identified and removed from the core. The investigations were corroborated by visual inspections. Two of these events were associated with specially made test fuel assemblies. In these cases, both the design and inadequate quality control system were identified to be root causes. The other three fuel element failures were related to the lack of adherence to the manufacturing process of standard fuel elements and subsequent failure to identify this deficiency during the quality checks.

Several reports described issues linked to failures of target capsules during or subsequent to their irradiation period. Some event investigations identified that a possible cause was a deficiency in implementation of quality control during cold welding process of the container. Another case indicated that a gas sample container contained an amount of gas that exceeded the allowable limit. This led to the container over pressurization due to irradiation and heat, and subsequent release of radioactive gas. Another event reported the failure of the capsule cover containing ^{235}U target material for production of ^{99}Mo. The failure occurred during irradiation in the reactor, and poor welding and insufficient quality control of the capsule cover were identified to be the root causes. The event caused the release of fission products into the cooling water system of the reactor. The event occurred in a reactor where several irradiations of similar targets have been performed.

Another event identified that an inadequate change control process led to a failure of the failed fuel detection system. At the time of the system installation and commissioning, a change of material that had not been appropriately documented, together with the lack of a monitoring programme, caused galvanic corrosion that severely damaged the components. The subsequent investigation showed that the redundant system also suffered the same problem.

A routine calibration of seismic sensors in a research reactor by a field calibrator showed them to be acceptable. The visual inspection, however, showed that the accelerometer masses were in a different position than recommended. Further investigations and testing on a vibration table revealed that the set points for a reactor scram under a seismic event were much higher than intended. The causes of the event were identified to be the defects in manufacturing of the sensors and inadequate field calibration procedure of the sensors. The procedures were modified, and surveillance intervals were reduced from 12 to 6 months. The event also revealed inadequacies in the field calibration and testing instrumentation to test full functionality of the sensors.

In an event during fuel shuffling, a fuel assembly was wrongly placed in a core position which was not cooled by gravity induced flow. The fuel assembly was supposed to be removed by the operator but could not do so due to a mistake in fuel manipulation. The reactor was started and operated momentarily before the error was identified. The reactor was then shut down, the fuel assembly in the wrong position was removed and quarantined, a different fuel assembly was placed into the correct location, and the reactor was restarted. The cause of the event was mainly due to personnel not performing quality control inspections and non-availability of formal self-checking or verification.

The tube of the fuel element integrity monitoring system was broken due to a manufacturing defect. The failure was discovered due to loss of primary coolant during operation.

The design of a research reactor required a drainage plug to be screwed and welded to the penetration lower base plate. The weld would prevent its removal and form a permanent seal barrier around the penetration orifice. However, this weld was not present. Several factors highlighting quality assurance related issues were identified during investigation. There were no records of deviation from the design requirements for the drainage plug weld, no records of non-conformance, or any justification of why this deviation from the design was accepted.

4.2.2. Safety significance

Failure of fuel elements is a safety significant event with consequence of release of fission products into the reactor coolant circuits or pools and possibly into the environment. Increased amounts of fission products in water negatively affect facility radiation levels and associated occupational doses; they also increase the risk of surface and personnel contamination in the case of spillage.

Shortfalls in quality assurance of the irradiation samples may result in damage of the target capsules with a potential release of its radioactive content into the irradiation system coolant or reactor pool water, with the same consequences as outlined above.

A research reactor with a fuel assembly placed in a wrong position may lead to operating the reactor outside operational limits and conditions (OLCs) and has the potential to result in fuel damage.

Manufacturing defects present in the primary coolant components due to the lack of quality assurance are likely to cause damage during operation of the reactor, giving rise to leakage of primary coolant and spread of contamination.

The violation of design requirements during installation and commissioning may lead to severe consequences if those violations remain undetected and unresolved.

4.2.3. Lessons learned

The following lessons are learned from the events reported in this category:

- Inadequate quality control of fresh fuel was the most common cause of events where cladding failure occurred. Using approved quality control procedures during the manufacture and post-manufacture fuel inspections can effectively minimize fuel failures during operation.
- Development of and maintaining an effective quality assurance programme is an important aspect in a good safety management practice. Its implementation throughout the operating organization will help prevent undesired release of radioactive material into the environment and assist the operating organization to achieve the occupational doses to be as low as reasonably possible.
- Ensuring adequate quality assurance during manufacturing and testing of components before installation has to be a necessary part of the management system [11].
- All safety significant activities involving core management need to be subjected to appropriate quality control such as verification checks.
- Effective implementation of a quality assurance programme ensures the proper installation and commissioning of research reactors in accordance with the design intent and configuration.

4.3. EXPERIENCE WITH HUMAN FACTORS AND SAFETY MANAGEMENT

4.3.1. Summary of the root causes

A review of the events reported to the IRSRR showed that approximately 37% of the events reported can be directly attributed to human factors and another 14% to inadequate safety management, which are included in this section. Attributes associated with human performance were identified in several other reports in the IRSRR database, where the primary causes of the events are different and have been included in other sections of this publication. The analysis of the events in this chapter shows that these events are mainly caused by procedure violations (non-compliance), inadequacies of the procedures, or errors of commission or omission on the part of the reactor operating personnel.

4.3.1.1. Procedures violations

In an event in a high power heavy water cooled research reactor, the long fuel elements are removed from the reactor in a guide tube inside a shielded fuelling flask with cooling on. While removing a clad-failed fuel assembly from the reactor, due to a bulged fuel rod, it could not be pulled inside the guide tube. The operators resorted to a non-standard procedure of pulling the fuel element without the guide tube inside the fuelling flask, resulting in the loss of cooling to the fuel element. Emergency cooling could not be provided as the interlocks prevented the movement of fuelling flask to another location where emergency cooling connections were provided. The event resulted in fuel disintegration and widespread contamination of the reactor building. The highest exposure to an individual was 190 mSv and a massive cleanup operation had to be carried out.

During an irradiation experiment with a fuel rod in an irradiation capsule, the fuel rod under test failed. The possibility of such an occurrence had been foreseen in the experiment design and safety report, and a special flushing procedure was prepared. However, the special flushing procedure was not used, and instead the standard flushing procedure was followed. This resulted in the spread of contaminated water from the irradiation capsule into the experiment cooling system.

A Pu–Be startup source was inserted in the core of a reactor before startup and removed after reaching a few watts of power level in accordance with the operating procedure. In this event, the operator forgot to remove the Pu–Be startup source and continued to raise the reactor power. This led to overheating of the Pu–Be source and the source was destroyed, releasing activity in the primary coolant. Significant efforts were required for cleanup of the primary cooling system.

The central beryllium block containing several irradiated ^{252}Cf targets was removed from the reactor for inspection in the hot cell. Reinstallation of this block in the reactor required the use of remote tooling. However, the operator carried out the operation by hand without the corresponding permission and safety measures. This resulted in the operator receiving an estimated 200 mSv whole body exposure, 50 Sv exposure to the right hand, and 15 Sv exposure to the left hand.

In another event, an experimental fuel pin was irradiated to a higher reactor power than planned, resulting in damage to the fuel pin. The event occurred because the reactor power was raised based on a faulty channel reading and other channels readings were not taken into account. Release of radioactivity in the cooling system of experimental set-up was reported.

During an experiment, a closed tank containing heavy water was placed between the core and the wall of the irradiation tunnel in a research reactor. The procedure required the tank to be removed after the experiment but was not followed by the operator. Due to overheating, the closed tank became pressurized and distorted. This resulted in the tank exerting pressure on the core structure. When an effort was made to remove the tank, it could not be removed. Finally, a hole was drilled in the tank to release the pressure and the tank was successfully removed.

An irradiated sample was being unloaded from the reactor into a shielded container within the reactor pool. As the crane was not functioning, the operators decided to remove the sample out of water without any shielding and put it into the shielded container outside of the pool. The shielded container was not designed to shield the activity of the sample. The event resulted in high radiation fields while removing the sample and around the shielded container due to insufficient shielding. A hot zone barrier was created around the shielded container to prevent personnel exposure and the radioactivity was allowed to decay. The personnel involved received avoidable doses, but no overexposure was reported.

Some events involving violation of OLCs included the removal of a fuel element from the core while the reactor was critical; not placing the faulty neutron flux rate channel in ‘Trip’ condition; and not complying with the reactor startup requirement in a pool type reactor wherein a basket used for preventing bypass flow around the fuel elements was not installed before the reactor startup. In all these events, the faults were detected, and corrective actions taken in time, thus preventing any significant consequences.

Two events involving improper positioning of the valves by the operating personnel were reported. In one event, following some maintenance work, the solenoid valve on the piping connecting the storage water tank and the main reactor tank, was left open instead of in the required closed position. This caused the water to flow from the storage tank to the main reactor tank, increasing the water level in the reactor tank and finally overflowing into ventilation ducts. The situation remained unnoticed for about an hour as no alarms were provided to detect high water level in the reactor pool. No radiological consequences were reported.

In a heavy water system of a research reactor, the procedure required a rubber diaphragm valve to be closed in stages to allow the thick rubber diaphragm to fully relax prior to making a good seal. During the event, the procedure was not followed, and the valve remained partially open. This operation was carried out to isolate a section of the piping for removal of a non-return valve for inspection. Due to inadequate isolation, when the non-return valve was removed from the piping system, heavy water leakage occurred.

The calculation to calibrate the neutronic instrumentation of a reactor was performed without using the approved procedures and was instead based on the experience and knowledge of the operating personnel. As a result, the calculation was inaccurate, and the reactor was operated at a power level greater than permitted by the OLCs. No safety limit was exceeded.

During a reactor startup, a scram occurred, and one control rod did not register as fully inserted. Investigation revealed that the control rod was damaged and had failed to insert fully into the core. The damaged control rod was removed from service and inspected. The damage had occurred because the control rod components, which are normally assembled using a variety of left- and right-hand threads, were assembled incorrectly by an inexperienced maintenance worker, without supervision. An approved procedure was not used.

4.3.1.2. Inadequate procedures

While conducting a surveillance test on the control and safety rods of the reactor, an operator misinterpreted the corresponding procedure and inadvertently inhibited the entire protective system of the reactor. The procedure did not clearly state which parts of the reactor protective system were to be inhibited and which parts were to remain operational, nor did it allow for the verification of features which had been inhibited and which had not. Additionally, the operator was not supervised, and had not received any special training, and due to a shortage of personnel, was performing the duties of both the primary reactor operator and the electrician.

In an event, during removal of the fuel assembly from the core, unknown to the operator, a fuel element detached from the assembly and was left in the primary cooling circuit. The procedure did not have any verification to account for the removed fuel elements. This element subsequently disintegrated and after several months the pieces became lodged in the primary cooling pump. Higher radiation fields on the primary pump revealed the event. No overexposures were reported but the primary system was significantly contaminated.

For removal of an experimental rig from the reactor, the procedure required that two control rods have to be fully inserted, so as to compensate for the changes in reactivity. During the event, while removing the experimental rig, the reactor became critical and scrammed, dropping the shutdown safety rods in the reactor. The investigations concluded that the control rods were not fully inserted, and the position indicator was faulty.

After a period of extended shutdown of the reactor, all three neutron detectors were positioned incorrectly, resulting in the actual reactor power being 2.3 times the indicated reactor power. The error was detected and corrected during low power operation of the reactor, thus preventing any power excursion.

Following maintenance that required the saw cutting of the primary cooling system pipes, the primary cooling system was not flushed. This resulted in metal particles being left in the primary coolant system. These metal particles became activated and resulted in higher radiation levels on the components of the primary cooling system.

A temporary heater was installed on charcoal filters of the ventilation system for the purpose of drying them. This activity was performed without any authorization or approved procedure. The filters caught fire due to overheating, and this resulted in the release of radioactive materials into the environment.

In one event, during an experiment to establish the safe time to be allowed for a plastic container to be used for sample irradiations, lead was placed in the plastic container to prevent the container from floating. The lead overheated and, due to a pressure buildup in the container, the lid blew off liberating the trapped gases, which caused bubbles and the reactor scrammed on short reactor period.

In one event, the transfer flask carrying irradiated samples was returned by the user without unloading the samples. When the transfer flask operation was being demonstrated to a visitor, the irradiated samples fell out. The samples were quickly retrieved, and since the dose rate was low, there was no overexposure of personnel. The deficiencies in clearly communicating that the transfer flask had been returned without unloading the irradiated samples, was identified as the main cause of the event.

An untrained contract worker picked up an irradiated bolt using a suction device from the pool and later removed it by hand without realizing the implications. When the area monitors gave an alarm, he dropped it back in the water. Although he received an insignificant but an avoidable dose.

In another case, a contractor carried out a repair of the spent fuel storage well using a metal grinder. A spark coming off the grinder caused smouldering of a rag left nearby after the ventilation system clean up. The smouldering rag was sucked into the ventilation system, causing the aerosol filters to smoulder. The analysis of the event identified the housekeeping and deficiencies in the procedures to be root causes of the event.

While moving the bridge over the reactor pool to perform a task in the core, the bridge contacted a light fixture in the pool and pressed it against the mechanical linkage of the flapper valve used to provide natural circulation cooling to the reactor. As a result, the flapper valve indicator was damaged, and the reactor trip associated with the indicator was disabled for one day of reactor operation.

A motorized valve was providing isolation during a maintenance task where a primary coolant pump was partially disassembled, however the valve had not been electrically isolated or locked out. During testing of a circuit breaker, the motorized valve was opened inadvertently. The primary coolant started draining from the reactor pool through the open pump casing. The isolating valve was closed after three minutes once the test of the circuit breaker was complete.

4.3.1.3. Errors of commission or omission

In a high power heavy water moderated research reactor containing multiple shutdown rods, an experiment was conducted to measure the reactivity of fuel elements. An operator manipulated the valves of the air system for shutdown rods, which raised some of them out of the core. At this time, other shutdown rods (called safety bank) were in the down position, maintaining subcriticality of the reactor. Another operator mistakenly pressed a wrong button raising the safety bank. This made the reactor supercritical, and the power rose in an uncontrolled manner. An effort to trip the reactor failed and finally the moderator was drained to terminate the event. By this time, all radiation levels were high, and personnel had to be evacuated. The reactor core and reactor vessel were damaged. Additionally, a large amount of radioactivity was released into the reactor building. Substantial doses were received in the cleanup and restoration phases.

In a critical assembly, the operator decided to reconfigure the core without an approved procedure in an attempt to save time and ignored the requirement of dumping the moderator fully before movement of fuel elements. During fuel manipulations, the reactor became supercritical. The energy released was 10 MW with a peak power of 200 MW. The operator received an absorbed dose of 21 Gy gamma and 22 Gy neutron and died within 48 hours. Other people received absorbed doses up to 0.25 Gy. Additionally, several of the core fuel elements were damaged.

An experiment was carried out to measure the power coefficient of reactivity during a fast power rise. The procedure required the experiment to be terminated by manually pressing the rapid shutdown button when the reactor period reached 6 seconds. Due to an operator error, the wrong button was pressed, causing a power excursion. 40% of the fuel elements were melted in the core.

In one historical event in the 1940s, with the control panel shut off, an operator raised the control rods, making the reactor supercritical. The power excursion was limited by a negative temperature coefficient. However, the operator received an effective dose of 25 mSv.

In one event, the supervisor instructed an operator to manipulate the control rods manually in a critical facility, thereby overriding the procedure of emptying the vessel before such operations are permitted. The operator was instructed to insert a control rod first and remove the other control rod later. He performed it exactly opposite. The reactor became critical and the power excursion was stopped by dropping a second control rod and emptying the vessel. The operator received a high effective dose of 5 Sv.

In one event, an experimental assembly was taken out of the reactor, leaving part of it in the reactor, partially blocking the coolant flow in one position. Later, a fuel element was loaded in that position and, due to reduced coolant flow, the fuel temperature reached the safety limit and failed. The event caused a release of radioactivity into both the coolant system and the environment.

In one event of the violation of OLCs, the operator set the overpower scram at 15% higher than the licensed power. The mistake was detected in a short time (11 minutes) after the reactor start up and immediately corrected.

In another case, a stainless steel wire tool was used for lifting a plug from an irradiation position while the reactor was in operation. Due to difficulties in hooking the plug and associated time, the wire tool was irradiated. The operator withdrew the tool from the reactor pool without any shielding. This caused higher radiation levels on the top of the pool and the reactor scramed. Subsequently, proper tools were designed, and the procedures were issued for such operations.

A maintenance task to replace a valve handle on the compressed air system at a reactor facility did not use an identical replacement part. The new valve handle did not align with the existing marks indicating the open and closed position. As a result, the valve was not closed fully and resulted in an unplanned water addition to the reactor pool.

During startup of a research reactor, it was discovered that the electrical jumpers that had been installed for a maintenance task during the preceding shutdown had not been removed. The jumpers electrically isolated valves that had an important safety role in the primary coolant system. The reactor was manually returned to a shutdown condition and the jumpers were removed.

Due to poor understanding of criticality safety requirements and procedures, during the routine inspection of fresh fuel in a reactor facility, quantity of fissile material larger than permissible was moved from the designated storage location to the inspection area.

A pump in the primary cooling system of a research reactor was reported to be noisy over a two-month period. An evaluation resulted in the decision to continue to operate the pump to the end of the cycle. Subsequently, the pump bearing failed, resulting in a low flow reactor trip, and a fire alarm in the pump room due to the generation of smoke.

During the process of shutting down at a reactor facility, secondary cooling was reduced by closing eight motorized valves, one for each heat exchanger, using a row of eight buttons in the control room. However, a trainee reactor operator inadvertently pressed the eight adjacent buttons on the control panel for the primary cooling circuit, initiating the closure of the pump isolation valves in the eight primary cooling circuits. The error was identified and reversed by the qualified control room supervisor.

During the infrequently performed operation to hoist a component out of a defueled core during a major outage, the operating personnel failed to notice that the hoist was not fully engaged with the component. The component fell from the hoist back towards the core, damaging reactor components.

Prior to transportation of irradiated isotope targets, the targets are placed in holders, and the holders assembled into a basket. The basket assembly utilized two parts of similar shape. In error, a basket was assembled using the wrong component for the base plate. As a result, one of the sample holders protruded from the bottom of the basket and was not noticed by operating personnel. When the basket was loaded into the transport flask, closing the flask's ball valve damaged the sample holder.

4.3.2. Safety significance

Many events related to human factors and the management of safety involved core management activities including experiments and illustrate the vulnerability of research reactors to such activities. The events related to human factors discussed in Section 4.3.1 sometimes occurred as a result of the operating personnel losing focus on the task being performed. In most cases, the operating personnel were not fully aware of the safety significance of their actions and sometimes, due to their previous successful performance of the same or similar tasks, failed to fully understand the risk associated with the task being performed. Some events, such as dropped material in the core region, could potentially cause significant damage.

Overall, the reported events are safety significant because the events were initiated or escalated by incorrect human actions and behaviours. Together with other contributors or combined with one or more latent organizational weaknesses, these events resulted in significant consequences, such as overexposure to operating personnel, core damage, component failure, spread of radioactive contamination, inadvertent criticality, fire, and violation of OLCs. In some cases, the events were terminated safely because the error was detected before it could escalate to a serious situation.

4.3.3. Lessons learned

For the accident leading to fuel disintegration, many of the problems would have been avoided if the reactor had been shut down and cooled for a few days, instead of unloading the fuel at power. It is noted that the interlocks, which were aimed to improve the safety, in this abnormal condition worsened the situation. In designing an installation, attention has to be paid to the behaviour of safety systems, also in abnormal conditions. Returning to a safe situation has to always be possible.

Achieving excellence in human performance requires an awareness of the risks associated with reactor operations. Identifying and minimizing the risk of human error and its impact on facility SSCs have to be the goal of all operating personnel. Regardless of how conscientious and careful people are, they can still make mistakes. Controls that reduce the chances of error include the use of human performance (error prevention) tools, as well as engineered, administrative, cultural, and oversight controls. The rigorous application of human performance tools aids in reducing the frequency of events.

Conditions at the workplace that can provoke an error are noticeable if people look for them. Error precursors are, by definition, prerequisite conditions for an error and, therefore, exist before the error occurs. Many conditions can provoke an error. The following error precursors are identified to have contributed to the events in the IRSRR database:

- Time pressure;
- High workload;
- Lack of knowledge;
- Insufficient supervision;
- Distractions or interruptions;
- Stress;
- Irreversible actions;
- Inaccurate risk perception;
- Overconfidence or complacency;
- Impulsive response or action.

The analysis of the events indicates that, if the operating personnel involved in these events had reviewed the procedures and verified the working conditions and/or environment, some of these events may have been avoided or the consequences of these events might have been lower.

A design change can reduce the likelihood of human error, such as preventing components from being interchangeable, or using removable covers for buttons on control panels with high safety significance, which require more deliberate action to activate the buttons, and reduce the potential for accidental use.

Events related to human factors and safety management demonstrate that managerial oversight and the timely communication of management expectations are instrumental in preventing events. In the recent years, the impact of organizational factors on human performance has become more visible, and the contribution of human and/or organizational factors to event is getting increased attention during investigations.

A mature safety culture at the facility, shared equally and enthusiastically by all operating personnel, is indispensable to recognizing and preventing a potential event. For the event where a motorized valve opened inadvertently draining the primary cooling water, the maintenance personnel had not ensured that the equipment was safe to work on, such as by de-energizing the valve and applying a lock to guarantee that de-energized state. In a facility with a strong safety culture, the isolation of equipment prior to maintenance is systematically included in work permits and maintenance procedures, and maintenance personnel will question conditions where isolation is not evident.

Many human performance tools such as self-checking, pre-evolution and job briefings, verification and validation, situational awareness and adherence to procedures are available to research reactor operating personnel. Utilizing these simple human performance tools, in most cases, would have prevented the reported events or lowered their consequences. For tasks with high safety significance, procedures can have human performance steps included directly into the work sequence, such as a requirement to pause and survey the work site prior to a critical step, or to request a measurement of radiation levels.

The significance of the human factors identified in the IRSRR review demonstrates a weakness in the safety culture of research reactor facilities. A strong safety culture requires that facility personnel follow approved operating procedures; however, many of the reported events showed that personnel were prepared to take short cuts in order to reduce the time taken or the complexity of tasks, without fully understanding the safety implications of the original instruction.

The implementation of the lessons learned from a significant event has been a contributing factor in the major improvements made in nuclear facility safety and reliability over the years. Key factors in preventing events are for facility personnel to exercise high standards of safety and to recognize and correct conditions adverse to safety by being able to relate such conditions to operating experience. It is important to reinforce the lessons learned and for those lessons to be incorporated into facility processes and procedures [11].

From the reported events where human factors had contributed significantly to the events, the following important lessons are learned:

- Complete and accurate operating procedures are necessary for the facility to operate within OLCs [12]. Periodic review of all operating procedures can help ensure procedures are as complete and accurate as possible.
- Safety requirements from higher level documents in the management system need to be systematically incorporated into lower level procedures, to ensure that requirements are met during work.
- Operating personnel need to follow procedures and be proactive in identifying improvements. When unexpected results occur during the performance of a procedure, operating personnel need to use caution and not engage in ad hoc troubleshooting.
- Supervisors need to focus on their oversight role and not engage in conducting the work.
- Operators need to be trained appropriately to understand the effects of their actions on reactor safety [13].
- The operating organization needs to adhere to high standards and not allow risks or poor conditions to go unrecognized or uncorrected.

4.4. EXPERIENCE WITH MAINTENANCE, INSPECTION AND PERIODIC TESTING

4.4.1. Summary of the root causes

A significant number of events analysed were related to maintenance, inspection and periodic testing. These events fall into the categories of mechanical maintenance, electrical, and maintenance related to instrumentation and control (I&C) systems.

4.4.1.1. Mechanical maintenance

Two facilities reported fuel damage resulting from, respectively, erroneous maintenance and lack of maintenance. In the first case, maintenance work on the core support grid was carried out with some fuel still loaded in the core. During this work, a long reach tool slipped causing it to mechanically damage the fuel cladding of one of the fuel elements. This was not noticed at the time but was discovered nine months later, after operating the reactor with the damaged fuel element.

Two facilities reported poor water chemistry (high conductivity). In the first event, high conductivity water from an exhausted resin bed in the purification system was entering into the primary circuit due to leakage past a faulty outlet isolation valve. In the second event at a different facility, a known leak of the water from the secondary cooling system into the primary system was allowed to persist for more than six months, resulting in detriment to the primary coolant system water chemistry. Eventually, the poor coolant quality caused fuel clad failure in several fuel assemblies and severe contamination of the primary system with fission products. In addition, practically the entire inventory of fuel in the core had to be removed from service as it could not be determined with confidence the suitability for further irradiation of the non-failed assemblies. Aside from the problem of high radiation inhibiting a close inspection, the fuel rods were also intensively coated with scale. Both events emphasize that priority should be given to repair and restoration to operation of out-of-service SSCs important to safety before other adverse impacts occur.

In another event, the quality of the primary coolant was seen to degenerate over time because the deionized water generator (supplying the facility make-up water) was being operated far beyond its manufacturer's recommended period of use. This was because maintenance of the deionized water generator had not been included in the facility maintenance schedules. There were also issues regarding the accurate measurement of the pH value of the water coolant. The corrective actions were taken promptly, thus avoiding any severe consequences.

Many events involved the failure of control rods. In one event, while shutting down the reactor after conducting measurements of neutron flux within the reactor core, one control rod failed to fully insert and became stuck at 33% withdrawn position. The other two control rods were fully inserted and were sufficient to shut down the reactor. After about 20 minutes, the stuck rod suddenly released and dropped to its fully inserted position. The prognosis was that grease in a sealed bearing in the drive mechanism had become hardened by radiation exposure and had made the bearing stiff to rotate. The problem was easily remedied in the short term by replacing the affected bearing. Similar events occurred 10 and 12 years previously, suggesting that, as a long term remedy, the maintenance programme on the control rod drives needed adjustment to take this information into account.

In another event in a different reactor, the control rod on a scram signal dropped in the reactor but its position indicator showed it to be fully out. The causes of the event were determined to be the slipped actuator cable from the cable reel, causing the rod to overtravel, and slippage of the rheostat gear (a position indicating device) from the axle of the motor. The maintenance procedures were revised to prevent recurrence. It is worth noting that a similar event occurred in the same reactor several years before.

Three events reported failures of the control rod drive mechanism, two of which resulted in a dropped control rod. In the first failure, the cable supporting the control rod fatigued where it passed over a pulley after a 30-year service life. The second failure was caused by shorting out the magnet assembly due to leakage from a failed o-ring seal on the actuator bellows. The third was caused by inadequate lubrication of the gears of the control rod drive mechanism. In each of these cases, the event could have been prevented if adequate maintenance and inspection had occurred.

At another reactor, a primary cooling system pool inlet valve and its actuator were removed for repair. The valve was put back in position, but the balance of work to complete the reinstallation could only be continued on the next day. On the following day, however, the maintenance team failed to recognize that the valve flanges had not been properly bolted and tightened and proceeded to install the actuator and control devices and to recommission the valve. The omission was discovered after another day, when the hold-up tank supplying the pool make-up water was found to be empty and about 38 m^3 of water flooded the valve pit. The event highlights the importance of a coordinated procedural approach, with checklists, when carrying out maintenance work on SSCs important to safety.

Three separate crane failure events were reported by a single facility over a time span of six years. Although all three events occurred while lifting heavy shielded casks containing irradiated material and resulted in the load dropping freely to the floor, each event was due to a distinctly different failure. In the first case, the crane brake failed to hold the load due to an improperly adjusted brake calliper. In the second event, the crane rope derailed from a pulley without a retaining guide, causing a 3 tonne container to fall six metres to the floor. In the third case, the severely corroded crane rope broke while hoisting a 20 tonne container filled with spent fuel and caused the container to topple over.

The latter case is particularly interesting because the rope was provided with a plastic coating to protect it from water ingress when used under water. The coating, however, had exactly the opposite effect, because it did not keep water out, but rather retained water that had leaked in, creating an environment within which severe corrosion was supported. The plastic coating also made it impossible to carry out a proper routine inspection of the rope. Notwithstanding this deficiency, the rope had been cleared by inspectors shortly before the event, who issued an unqualified certificate of health for the rope. The first and third of these cases indicate the need to improve maintenance work culture, while the second case was more a design deficiency with an elementary solution. It is notable that none of these failures resulted in breach of the containers or spillage of their contents.

At a research reactor facility, an inadequately tightened flange on a loop experiment resulted in leakage of primary coolant into the loop process compartment. This followed preventive maintenance work on the loop during which the flange joint was separated. Given that the operating parameters for the experiment were rather extreme (high temperature, high pressure), it was concluded that, apart from a lack of adequate quality control of work on a high technology piece of equipment, the maintenance team did not use the appropriate special tools and equipment needed for tightening the flange properly.

In another event, radioactive water leaked from the mechanical seal of the circulating pump due to a loose screw. The pump was overhauled prior to the event. The leaked water spread through cracks of the floor of the room to another room below causing spread of contamination. The event highlights deficiencies in the maintenance procedure of the pump and unnoticed cracks in the floor of the room. The corrective actions were taken to introduce double checks in the maintenance procedures to ensure proper tightening of the mechanical seal screws, installation of remote monitoring cameras for leakage, and repair of the floor to plug the cracks.

Inadequate maintenance on emergency diesel generators resulted in the failure of two out of three diesel generators to operate on demand at one facility. Although each of the two diesel generators failed for a different reason (one due to low oil pressure and the other due to high coolant temperature), the common thread in the failures was the lack of a coordinated maintenance programme on the diesel generator units.

Two events involved primary pump failures due to motor pump coupling failures, resulting in reduced primary flow. One was caused by the embrittlement and fatigue cracking of the bearing box fixing screws. In the other, the primary coolant motor pump coupling broke due to excessive vibration and its inlet valve was damaged. The maintenance programme did not include vibration monitoring of the rotating equipment.

Other mechanical maintenance events at various facilities include: water leakage from a control rod seal due to inadequate preventive maintenance; overexposure and breakage of irradiation containers on failure of the transfer system due to the lack of maintenance, or maintenance at too low frequency; and leakage of pool water at two separate facilities due to poor maintenance on demineralizer equipment. The last of these makes an especially important point, in that maintenance personnel are not always sufficiently aware of the consequences of leaks or improper alignment of valves in the demineralizer section of the facility, which is generally away from the reactor.

One of the events reported that, due to the absence of vendor data regarding the quality of welds, a radiographic inspection programme was initiated to evaluate all the welds in the primary system, including the reactor vessel. A number of significant defects were found, some of which could have led to a loss of primary coolant accident if the welds failed. This prompted the installation of measures to limit the loss of coolant should the welds fail, as well as the implementation of a more rigorous routine inspection programme aimed at establishing the stability of the weld defects.

At another facility, the failure of a nylon rope used to support a 350 kg loop experiment device in the dismantling cell caused the device to fall nine metres, resulting in the damage to the device beyond repair. Fortunately, the activated contents (experimental fuel) had already been removed from the device, and the radiological consequence was trivial. This highlights the need to use appropriate lifting equipment for heavy loads and to ensure the health of the equipment before using it.

In another event, the power supply cable of a motor driven trolley used for moving experimental facilities was slack due to weak tension. This caused the cable to fall on the rails and during movement of drive trolley, the cable got damaged. The investigations revealed the deficiencies in the cable mounting and lack of proper surveillance to detect such deficiency before using the drive trolley. The repair of the drive trolley caused unnecessary dose to the maintenance personnel, as the drive trolley contained an irradiated experimental device at the time of the event.

An event at another facility resulted in a collapse of the secondary cooling tower. The initiating event was winds from a tsunami. While this is an external event, the design was rated for the wind load that was experienced. The resultant failure was due to inadequate maintenance and inspection of the tower supports. During an extended shutdown, the cooling tower was not inspected, and the lack of use allowed deterioration of the wooden supports.

4.4.1.2. Electrical maintenance

Several events reported to the IRSRR are related to deficiencies in electrical maintenance activities. One event was due to failure of a control rod to insert (scram) due to a short circuit in the electromagnet wiring, which inadvertently maintained the current to the magnet coil after the scram relay had opened. The second failure resulted in a secondary coolant pump to stop on demand due to the arcing-closed of the power supply contactor relay. In the third event, an emergency diesel generator failed to start after a disruption of off-site power due to the undetected failure of both starting relays. A fourth failure was in an overhead crane, which lost the ability to move vertically during use due to failed limit switches. All of these events occurred mainly due to inadequate or ineffective maintenance.

4.4.1.3. Instrumentation and control maintenance

Four events reported to the IRSRR are related to deficiencies in I&C systems. At one research reactor facility, a repeated failure caused a newly installed digital instrumentation system to display improper positions of two control rods. The approach described in the event report followed a trial-and-error approach over a period of two years before the problem stopped recurring. This highlights the need for proper training of technicians when new technology is introduced to a facility and, more importantly, the need for their comprehensive understanding, not only of the new technology, but also of its impact on the safety of the facility.

In two events, neutron detector failures caused the flux monitoring equipment to give an inaccurate indication of the neutron flux during operation. In the first event, a coaxial signal cable was found to have deteriorated due to radiation exposure. The second failure was due to moisture intrusion inside the detector chamber that caused spurious scrams due to erratic indication of the neutron flux. The maintenance programme did not have any schedule for replacing the cable or inspecting the detectors. The maintenance schedule of both facilities was adjusted to include pre-operational checking and surveillance procedures with maintenance schedules with proper quality assurance.

In one event, an integrated circuit failed in the pneumatic transfer system for radiation samples, rendering the system inoperable. The component was not periodically inspected, because the component was part of an auxiliary system in an inaccessible area, so it was not incorporated into the periodic inspection and monitoring programme.

4.4.2. Safety significance

Fuel failures, actual or potential, are events of important safety implications. In the two events reported where fuel damage occurred, the damage was preventable by appropriate maintenance actions or better understanding of the implications of inadequate maintenance.

Failure of control rods to insert in the core is always a potentially safety significant event. The reported events showed that an adequate preventive maintenance programme would have prevented these events.

Dropping of heavy loads often results in damage to the dropped items as well as to other interacting items.

In the report on the implementation of a surveillance and monitoring programme, potentially serious safety consequences in future have been eliminated by ensuring an in-depth understanding of component ageing, corrosion and degradation of material and weld defects, and taking timely measures to mitigate their failure.

Spillage of primary coolant within the controlled areas in a facility does not generally lead to excessive exposure of personnel or threat to the environment; however, the events indicate that some leaks can remain undetected for long time.

A maintenance, inspection, and periodic testing programme that is not comprehensive, i.e. in which some safety related components and subcomponents are not covered, could lead to non-availability of the equipment when needed.

4.4.3. Lessons learned

The lessons learned from the events reported in this category are the following:

- Historical failure data is invaluable for adjusting a maintenance programme to prevent the recurrence of an event.

- Statutory inspection and testing of lifting equipment (and other material handling equipment) cannot be compromised by modifications made to address application specific problems. Both inspection and periodic testing have to be conducted to complement each other [14].
- Where high-technology equipment is maintained, maintenance personnel need adequate training and appropriate tools to work on such equipment.
- Provisions for water leak detection has to be available, particularly in the normally unattended areas of the facility.
- Equipment that is out of service or degraded needs to be restored to service as quickly as possible to avoid further operating complications.
- Post maintenance checks, including appropriate facility inspections after outages, are as important as the maintenance work itself.
- A comprehensive maintenance programme that includes all subcomponents optimizes equipment availability.

4.5. EXPERIENCES WITH AGEING OF STUCTURES, SYSTEMS AND COMPONENTS

4.5.1. Summary of the root causes

Ageing is a general process in which the characteristics of SSCs gradually change with time or use [15]. This process eventually can lead to failure of SSCs in performing their intended function. At research reactor facilities, many ageing issues develop or exist that require special attention in refurbishment projects through the implementation of an effective ageing management programme.

Applying this distinction, events from the IRSRR where ageing of SSCs is identified as the main cause are discussed in this section. These events ranged from as early as 1980 right up to some of the most recent ones.

Two events of failure due to the degradation of electrical insulation in the windings of control rod electromagnets and primary pump motors, respectively (the first of these reported twice, four years apart), were reported. These events were easily remedied by the replacement of the failed components, which suggests that the real issue is non-adherence to the service lifetime of such equipment. It was noted that the failed primary pump motor had seen a long service life without any maintenance or inspection. However, it was also noted that the replacement motor was given a revised insulation specification to have an extended service life with improved reliability.

Three events of failure of SSCs due to fatigue were reported: failure of fasteners used to connect two parts of a transient rod of a pulsed reactor; cracks appearing in a perforated flow diffuser plate below the core of a high flux reactor; and shearing of a shaft of a secondary coolant pump. In the first case, it is more likely that the fatigue described is the result of a breach of procedure or deficient quality control during assembly of the transient rod (e.g. an undetected manufacturing flaw in, or overtightening of, the failed screw). The report regarding the sheared shaft of a secondary coolant pump does not give any information about its service life before failure, nor on the condition of the pump bearings, impellor or other components that could have contributed to the failure. Such failures could be caused by high vibrations due to various reasons, such as imperfect alignment of the pump or motor assembly, or poor material quality of the shaft, bearing or impellor seizure.

In another event, after a leak was noticed during visual examination of the primary reactor piping, it was revealed that a welded joint in the primary piping was damaged due to ageing and accumulation of stresses over time during operation. As a result, the management of the operating organization decided to replace all affected and similar parts of the primary piping.

Due to years of continuous fatigue, the teeth of the clutch gear of one of the secondary cooling pump motors were degraded. This resulted in disconnection of the pump drive motor shaft and the pump impeller coupling resulting in loss of flow. Repairs were made by replacing the pump motor clutch with a new one. The reactor could not be operated because of the inoperable cooling system.

Most of the events in this category are related to leaks or failures due to corrosion. Many of these are associated with corroded piping, both inside the facilities and outside buried in earth. Two reactors experienced corrosion and leakage of pneumatic system transfer piping, which led to spillage of primary or pool water within the facilities. Two other reactors experienced leaks in the primary coolant systems, one due to corrosion of the main primary piping buried underground (suggesting an inadequate design) and the other due to corrosion of the entombed decay tank. The latter case is especially important from a design perspective because, while the decay tank is almost inaccessible for maintenance and inspection, the concrete enclosure allowed the ingress of rainwater. In addition, the vent pipe connection to the aluminium decay tank was of galvanized carbon steel piping and the vent pipe penetration out of the enclosure provided a primary (although not the only) pathway for the ingress of rainwater. In one of the events, the leak originated from buried steel piping of a non-safety grade secondary experiment cooling loop that was corroded while the piping was in use since the commissioning of the reactor about 60 years prior, without inspection. The secondary piping was replaced to fix the leak issue. In another event, during routine testing, a primary system butterfly valve could not be positioned. The cause was determined to be the corrosion of the valve body which made the axle of the valve stuck.

In a research reactor facility, a buried wastewater line provided for the transfer of both contaminated water to storage and uncontaminated wastewater to a sea outfall. The alignment of the line for one or the other function allowed a quantity of contaminated water trapped in the line to be flushed out to sea with the uncontaminated water during that activity, which suggests an important oversight in the design of the systems. Added to this, the outfall line corroded and leaked, causing serious contamination of both the ground and groundwater in the area. Levels of dose rate up to 7 mSv/hr were measured in the ground, and local vegetation samples indicated ^{137}Cs uptake.

One facility reported uncoupling and dropping of a control rod during power operation due to the buildup of corrosion products between the armature and stator parts of the electromagnet coupling device. The nickel phosphate plating over the magnetic iron components showed signs of excessive degradation or wear, which was suggested to have originated from the excessive polishing of the components by maintenance staff over many years. This led to the exposure of the iron substrate to the environment and the development of corrosion. The event report did not establish why the operating environment for the electromagnets promoted corrosion, but confirmed that the affected components were cleaned, re-plated and placed back into service with an enhanced maintenance and testing programme.

One research reactor facility reported the degradation of the ceramic tile liner of the pool structure, to the extent that a leak path was present which led to the contamination of groundwater. A maximum specific activity of 170 kBq/l was measured in the groundwater. The reactor was shut down for two years to replace the ceramic tile liner with a metal liner (type of metal not specified), to eliminate the leak.

Corrosion of the reactor vessel and subsequent leaks causing loss of coolant was described in the report by one facility. In this case, the cavity between the reactor vessel and the concrete structure was filled with sand, but not according to the designer's specification. Wet sea sand had been used instead of dry river sand. The result was an environment very conducive to corrosion. Consequently, the vessel wall had become perforated in several places. These were repaired with patches and the sand replaced by sand of the correct specification, but the event highlights the need for a vigorously applied quality assurance programme during construction and subsequent periodic inspection and assessment of the SSCs.

In one event, while reinstalling the pneumatic transfer system after more than two years of being out of service, tests were performed to check air pressure and possible air leakage. However, these tests caused a release of contaminated air within the laboratory. The valves of the pneumatic transfer system were corroded and released particles of copper and zinc into the system, which were falling into the radiation position of the pneumatic transfer system. There, the particles were activated during reactor operation. These activated particles were released from the piping during the test. The degraded components were replaced later. This event was attributed to the lack of ageing management and maintenance.

During a maintenance activity at a research reactor, a leakage from a valve was detected. The leakage was caused by a broken valve membrane. It was revealed that valve membranes were neither checked nor replaced for more than 40 years.

During a routine inspection, the carbon steel fuel piping of the diesel generator set was found corroded. Further investigation involved inspection of all fuel piping of all three diesel generators at the facility. The carbon steel fuel piping was subsequently replaced with a stainless steel piping. The diesel generator sets supplied emergency power and the timely detection led to the corrective action before any abnormal event.

Other events in this group were: deformation of a lead block shield at a thermal neutron column due to thermal creep; broken beam port ventilation pipe due to corrosion; radiation ageing of non-nuclear-grade water level switches used to stop a reflector cooling and purification pump (to protect the pump), which in turn caused a reactor scram on several occasions in short succession; graphite reflector elements jammed together in the core due to neutron dose related deformation; and perforation of a pool liner by corrosion from the concrete side of the liner due to trapped moisture.

4.5.2. Safety significance

The reported events showed that degradation and damage of SSCs important to safety due to ageing is safety significant because they may result in disruption of cooling flow, reduction in heat removal from the core, inoperability of valves, and release of contamination.

Ineffective ageing management programmes have led to contamination of the ground and groundwater around the facilities in two events. Such situations take a long time and require significant efforts to mitigate the effect of events. In a few cases, the reactors had to remain shut down for long periods to remedy the situation arising from the failed SSCs due to ageing.

4.5.3. Lessons learned

The lessons learned from the events reported to the IRSRR in this category are the following:

- Establishment of a systematic and effective ageing management programme as early as possible in the lifetime of the reactor significantly contributes to preventing events and the resulting consequences.
- Maintenance programmes have to consider ageing degradation of SSCs.
- Increased attention has to be given to inspection and testing of SSCs important to safety.
- Inspection and condition monitoring programmes need to be carefully developed for SSCs to capture ageing effects in a timely manner, particularly for components under continuous stresses or fatigue.
- Replacement programmes need to address ageing related degradation of SSCs and proactively consider inaccessible SSCs particularly related to SSCs prone to corrosion under harsh environments.
- Quality assurance of manufactured items, even those that are commercial off the shelf items, is paramount when procuring spares for a nuclear installation.
- Corrosion is one of the main causes of ageing degradation and it does not only occur in the obvious places. In-service inspection activities have to take this fact into consideration.
- A new reactor is not immune to early ageing effects. This is especially true for instrumentation and electrical items.
- The service lifetime of SSCs, especially for items important to safety, has to be determined, ideally during the design phase, and has to be taken into account in the maintenance programme.
- Design and operating procedures for liquid waste handling systems, especially those that are buried and cannot easily be inspected, have to be scrutinized for errors in design or operating logic that could lead to hazards in the environment or public domain.

4.6. EXPERIENCE WITH INADVERTENT REACTIVITY INSERTION

4.6.1. Summary of the root causes

In the history of research reactors, a significant number of uncontrolled reactivity addition events have happened. Most of them occurred during the early years, when nuclear reactors themselves were still under development and the safety standards had not matured.

In case of a sufficient negative temperature reactivity coefficient, the result will be a more or less limited power increase. However, if the reactivity increase is not compensated inherently by such feedback effects or by a protection system, such as the drop of control rods or the removal of a moderator, the damage can be severe. In the reported events, reactivity insertion was caused by one of the following:

- Withdrawal of absorbing material, most of the time one or more control rods;
- Addition of fissile material;
- Addition of a moderator or reflector material;
- Malfunctioning of control system instrumentation.

Four events of uncontrolled withdrawal of a control rod are reported to the IRSRR, with different consequences.

In one case, during a reactivity measurement activity, a control rod which was partially in the core was withdrawn by an operator, provoking a positive period of about 0.25 seconds. The safety system did not respond during this period and a power excursion occurred. However, the reactor was shut down due to quenching by the Doppler effect, without damage to the core.

In another case, during an experiment to measure the reactivity worth of fuel elements, a bank of control rods was withdrawn due to operator errors and, upon giving a trip command, three of the four control rods of the safety bank did not drop fully in the reactor. This caused a power spike which damaged the fuel and led to a steam explosion. Further damage was caused by a hydrogen explosion. The reactor was shut down by dumping the moderator. The whole reactor core was destroyed, and the reactor building was severely contaminated. However, the radiation dose for the workers and the release of radioactive material into the environment was limited.

A severe reactivity insertion accident occurred in an experimental reactor loaded with highly enriched uranium fuel in a vessel. The core was composed of 40 fuel assemblies and 5 control rods in crucifix form. One of these control rods was placed in the centre of the core and the other four around it. During a shutdown for maintenance, the control rod shield plugs were removed in order to install flux measuring wires. The day before the scheduled restart of the reactor, the control rods had to be reassembled, requiring lifting of the control rod by around 10 cm. The operator lifted the central control rod far beyond the specified 10 cm, making the reactor prompt critical. This provoked an exothermal aluminium–water reaction and steam explosion, causing the vessel to move upward. Three operators present in the reactor building were affected by the blast; two operators working just above the reactor were killed immediately, with the third dying shortly after his evacuation from the reactor building. The accident caused significant contamination of the environment. The root cause analysis showed several design deficiencies that include the requirement to lift the control rod for assembly and disassembly, the reactor becoming critical with the removal of the single central control rod, no mechanical limit while withdrawing the control rod manually, use of burnable poison in control rods that caused rapid reactivity gain, and reduction in shutdown margin over the core lifetime.

In a heavy water moderated and natural uranium fuelled critical assembly, the reactor power was controlled by heavy water level and cadmium rods were used for shutting down the reactor. At the time of the event, an experiment of activating foils was being conducted. The heavy water level was raised to reach criticality. Out of three neutron detectors (BF_3 chambers), two were showing similar values while the third one showed an erratic reading. Not realizing the impact of their action, the operators disconnected the third detector and continued the reactor operation. One of the experimenters smelled ozone and the reactor was shut down after a few minutes. Later investigations showed that two chambers believed to be reading correctly had saturated and the reactor operated at unknown power. The six persons present received high effective doses (ranging between 2.05–4.33 Sv); one died and the other five recovered after serious sickness.

A few more reports discuss events due to the insertion of material, causing an increase of the reactivity of the core. Most of these events occurred in the early years during experiments studying the criticality phenomenon itself. The root cause of these manipulation errors was the lack of knowledge of how criticality occurred.

One event happened during more recent years. In a nuclear reactor, criticality is achieved by a combination of insertion of fuel elements and withdrawal of control rods. During the loading of the reactor core with fuel elements, a power excursion occurred. After the loading of five fuel elements, the control rods were withdrawn to check the criticality. The procedure required the control rods to be withdrawn to 40%, but the rods were driven to the 85% withdrawn position. On insertion of the sixth fuel assembly, a blue glow (Cherenkov radiation) was seen, and the reactor tripped on overpower. The protection against a too short reactor period was bypassed at that time to avoid spurious trips while moving irradiated fuel into position for loading into the core. The bypass had not subsequently been normalized. The power excursion caused no damage or personal injuries. No radioactivity was released. The causes of the incident were inadequate application of the loading procedures and failure to bring the reactor to a safe condition before further fuel loading was done.

In a high power research reactor, during power ramp up using the automatic power control system, the control rod motion was inhibited due to the actuation of the control rods movement protection interlock. This caused a slight reduction in reactor power. When the operator reset the interlock, the power suddenly rose beyond the scram value and the first reactor protection system did not function. Reactor was scrammed by the independent second protection system. The cause was a saturated amplifier in the control circuitry due to a combination of high neutron flux and high rate together. This led the control system to detect lower power, thus allowing the automatic power control system to raise the power suddenly. The potential for this scenario was neither analysed nor tested.

4.6.2. Safety significance

All events related to inadvertent reactivity insertion are events of potentially high safety significance. The consequences of an uncontrolled reactivity increase are often severe and have resulted in significant exposure of operating personnel to radiation, radiation release into the environment, and contamination spread within and out of the reactor facility. Among the events reported to the IRSRR, these are the ones where injury or death as a consequence have been reported. These are also the events where reactors have been destroyed beyond recovery. The events also highlight the importance of an independent second shutdown system in certain research reactor designs.

4.6.3. Lessons learned

Accidents due to inadvertent reactivity insertion occur suddenly and without any preceding warning. As the reported events show, the shutdown, startup, and low power operation states of the reactor have a higher risk for reactivity accidents than in the operational steady state.

The reactivity insertion accidents are rather independent of the reactor power. Many of the reported accidents happened with critical facilities or with the reactor at low power. Research reactors are sensitive to this kind of incident, due to the large number of manipulations which are done, often with fuel elements with a high uranium enrichment. In research reactors, the insertion or withdrawal of irradiation samples at power can also add significant amounts of reactivity.

The following lessons are learned from the events reported to the IRSRR under inadvertent reactivity insertion:

- Handling of material that can cause reactivity changes (fuel elements, control rods, reflector elements) has to be performed according to approved operating procedures [16]. These procedures have to be analysed by persons with sufficient knowledge on criticality before they are carried out. Deviations from procedures have to be implemented by means of a properly analysed revision of the procedure.

- The operating personnel have to be trained in using these procedures and have to be aware of potential consequences of deviating from them. They have to be knowledgeable about the safe condition of the reactor. In addition, they have to be given the opportunity to ask questions if they are not confident.
- It has to be taken into account that human errors can always occur. One of the solutions is to introduce a double check of the safety significant operations, where one operator checks the work performed by another operator. Human errors have to be considered in the design of the reactor protection and control systems as well as in the operating procedures dealing with handling fuel and core components or other reactivity control elements.
- It is preferable to have a diverse reactivity control system, such as dumping the moderator or a second system of absorbing material. This has also to be considered during the design of an experimental device, which can cause significant reactivity changes. In some cases, inherent safety aspects can be taken into account, such as the high negative temperature feedback of uranium zirconium hydride fuel used in TRIGA reactors. The events also highlight the importance of an independent second shutdown system.
- Saturation of signals due to either the detectors or the electronic characteristics of the control system in a particular operation scenario can cause an uncontrolled rise in reactor power. The design needs to take into account all such possible scenarios.

4.7. EXPERIENCE WITH UTILIZATION AND MODIFICATIONS

4.7.1. Summary of the root causes

In many cases, utilization of a research reactor changes during its lifetime. New experiments are introduced, and irradiation programmes are changed as a consequence of different demands. These changes can introduce new risks which have to be evaluated. A number of events were reported to the IRSRR on damage of materials during irradiations and problems with experiment holders and devices.

4.7.1.1. Failure of the irradiation capsule

An incident of a TeO_2 capsule burning in a thimble tube was reported, in which 3.7×10^{11} Bq of ^{131}I was released into the pool and an estimated 1.85×10^{7} Bq of ^{131}I into the environment. Two operators involved in the transfer of the thimble tube after the incident inhaled ^{131}I, and the estimated doses to thyroid were 0.8 mGy and 0.5 mGy, respectively. In another case, a quartz capsule with an organic irradiation sample broke. This created a gas bubble which replaced water. Due to the reactivity transient, the reactor power increased. This resulted in a fast neutron flux increase and reactor scram due to overpower.

Some events reported damage to experimental fuel assemblies that failed and led to fission product release. In one particular case, a fuel element was instrumented with thermocouples to study the relationship between fuel cladding temperature and neutron flux. In order not to disturb the water flow distribution around the fuel element, grooves were cut for placing the thermocouple. This weakened the cladding, and the fuel element failed following a fast temperature change. An estimated 5.9×10^{13} Bq of noble gases and 3×10^{13} Bq of iodine was released into the coolant system, and 1.85×10^{13} Bq of noble gases and 1.85×10^{7} Bq of iodine was released into the atmosphere.

Two events involving failure of containers with irradiated biological samples occurred in the same reactor within a span of a few days. In the first event, a sample contained in a quartz glass container was dropped inadvertently from the reactor top platform to the reactor hall floor and broke. This resulted in the contamination of the floor and took more than 10 days to decontaminate. In the second event, the sample container exploded while handling and contaminated the reactor hall floor again.

Another event reported partial meltdown of a fuel element when reactor power was raised from 30 MW to 43 MW as part of a test. The reactor scrammed on high ^{16}N activity in coolant and radiation levels increased in the coolant system and ventilation system. The subsequent investigations revealed that the possible cause of fuel failure was the flow blockage due to foreign material. It was suspected that the material blocking the flow could be the pieces of dry paint that peeled off from the reactor pool walls. In this event, all safety systems functioned as intended and no significant exposure was caused.

Another flow blockage event occurred in the pneumatic transfer (rabbit) system due to foreign material ingress into the experimental loop. The obstruction blocked the cooling flow to the experiment capsule and the capsule failed, releasing radioactive material into the experimental loop and increasing the radiation fields in the vicinity. The material blocking flow was discovered to be plastic sheeting.

4.7.1.2. Failure of a holding or irradiation device

A number of events were caused due to problems with the holding or other devices associated with irradiation facilities. In one event, a long shielding plug was introduced into a short, air-filled, horizontal thimble forcefully. The action caused the thimble to rupture, leading to a reactor pool water leak. Fortunately, the plug was not fully ejected, and the operating personnel quickly stopped the leak.

In another event, flooding of the rotary specimen rack of a TRIGA reactor during its operation caused the neutron flux registered by detectors to be affected by this additional water volume. This was not anticipated by the operators who controlled the reactor according to the indicated power readings and, therefore, operated the reactor at a power level higher than allowed. In a fast reactor, an irradiation device was found to be mechanically damaged by malfunction of a fuel handling machine.

In one event, failure of a ^{124}Xe capsule holder caused the capsule to float in the reactor pool and caused the reactor to scram due to high radiation levels on pool top. The corrective actions included a modified design of the irradiation box and the holding tool.

When new irradiation devices are introduced, unforeseen situations can happen. One event reported leakage of primary water due to a break in an envelope for the irradiation of uranium targets for ^{99}Mo production. The break was caused by severe vibrations in the target holders. The inner structure was redesigned to avoid these vibrations and a periodic inspection programme was defined.

In another event, in a pneumatic transfer system, a wrong valve configuration caused the active air to be released, which contaminated the reactor hall floor and seven persons involved in the testing. The investigations showed the weakness in design (valve positions indicators were not provided), and testing was conducted without proper planning and supervision.

In one event, experimenters used an ad hoc procedure and a poorly maintained handling tool to irradiate a capsule of ^{153}Sm. During removal of the sample, the sample holder was dropped.

The capsule broke, releasing the material into the reactor pool. This resulted in unwanted contamination of the reactor pool and unanticipated radiation exposure to operating personnel.

4.7.1.3. Irradiation of the samples at wrong power or wrong irradiation position

A number of events occurred due to wrong irradiation conditions. In one event, an operator loaded an ethyl bromide (C_2H_5Br) capsule into an activation tube of the reactor while the reactor was operating. He quickly noted that the capsule was not properly placed due to a short bottom capsule placed below the sample instead of the long one. The operator removed the sample and placed it in a shielded container. While removing the short bottom capsule, the aluminium head of the pick-up device was activated and caused a radiation alarm when it was lifted to the pool top level. The operators did not immediately identify the source of radiation and attributed the alarm to a leak in ethyl bromide capsule, an event which had previously occurred. It was only after a certain time that the pick-up device head was identified as the real source of radiation, after which it was lowered below the pool water level to decrease the radiation level.

In another event, an irradiation capsule filled with xenon was loosened from its holder and started to float, causing a radiation alarm at the pool top level. One more event reported the irradiation of an experimental fuel pin at the wrong power due to miscalculation of the neutron flux shape factor. In this case, the fuel was irradiated at too low power and so no damage was done, but just as easily it could have been irradiated at higher power level with undesirable consequences.

4.7.1.4. Improper modification of an experimental device

In one report, renovation and modification work on a beam collimator resulted in partial dismantling of the beam stop that provides radiation shielding. This occurred during a major modification to replace the existing collimator and partially removed part of the beam stop which is a device designed to absorb the energy of the energetic gamma beam. The beam stop was not readily visible due to a concrete structure and pre-operational radiation surveys did not reveal the anomaly. The issue was only discovered when an individual's electronic dosimeter alarmed when passing by the outside of the reactor building.

4.7.2. Safety significance

The consequences of the events for irradiation capsules and holders described in Section 4.7.1 were usually limited due to the small quantities of material involved. It is noted that an activated aluminium capsule can be a greater source of radiation field than the sample material itself, especially immediately after removal from the reactor core. In a number of cases, the events led to unnecessary (although not excessive) doses to the operating personnel or to contamination of personnel and/or work areas. However, the consequences of such events could be more severe if chemically reactive or hazardous materials are irradiated. For the beam collimator event, significant radiation exposure was possible due to the unexpected high radiation field outside of the reactor building.

4.7.3. Lessons learned

The discussed events show that due care has to be taken when materials are to be irradiated in the reactors. The following lessons can be learned from the events reported to the IRSRR in this category:

- In case of introducing new irradiation programmes, a safety assessment in accordance with the safety significance of the programme is essential [17].
- Irradiation devices have to be designed to minimize the risk of damaging the irradiation capsules due to overheating or mechanical damage, and accidental release of capsule from the device.
- Irradiation devices have to be regularly inspected and maintained, with the same attention as the reactor components themselves.
- Handling of irradiation samples has to be performed in accordance with approved procedures. Attention has to be paid to unforeseen recovery actions by operators which can sometimes make the situation worse.
- Modifications to experiments and experimental devices need to adhere to a management system process which ensures radiation characteristics are well-known and controlled following modification, and include proper authorization and oversight of experiments, experimental devices, and utilization [18].

4.8. EXPERIENCE WITH RADIATION PROTECTION SYSTEMS AND PROCEDURES

4.8.1. Summary of the root causes

There were several events in the IRSRR database that involved overexposure of operating personnel to ionizing radiation. Those reports are addressed in other sections of this publication as the over exposure was the result or consequence of other cause(s). The events reported in this category are the ones in which the operating personnel received unnecessary doses mainly due to non-adherence to the established radiation protection procedures.

In one event, the personal dosimeter of a maintenance officer recorded a high value of 35 mSv over a two-month period. The investigations revealed that the accumulated dose was due to storage of the dosimeter on a desk in a maintenance laboratory, in the vicinity of an activated instrument connector. Presence of the activated component was unknown to the persons working in the area and radiation protection staff. The actual dose received by the person was estimated based on the occupancy time in the area. The event highlighted the need to strictly enforce radiation protection procedures that include storage of dosimeters at designated places, periodic checks for detecting unknown radioactive materials in high occupancy zones, and reinforcement of radiation detection of materials at the exit of the controlled zone.

In another event, a lab coat of the reactor operator was detected to be contaminated. The event came to notice after a radiation alarm was triggered. The immediate investigation revealed that the radiation level within the reactor building was normal, and the source of the lab coat contamination was external to the reactor building. Later, it was found that the lab coat used by the operator had been brought from another nuclear installation located nearby.

In two events, a worker received a high radiation dose to the hands. In one event, the worker was involved with the handling of samples used in the neutron activation analysis laboratory. The cause of the event was determined to be manual handling (by hands) of the irradiated samples, while the procedures required the use of tools. In another event, a worker had been carrying a sealed radiation source attached to the end of a rod. During transport, the worker set the rod down. The worker picked the rod back up by the wrong end, so that the source itself was in the hand. The worker’s electronic dosimeter was out of service, and a gamma radiometer was not worn, so the worker was not alerted to the exposure.

In one event, personnel present in the reactor hall were contaminated due to the presence of high airborne activity. The source of high activity in the air was determined to be a failed fuel element in the core, releasing fission products into the pool water. The alarm set points of radiation monitors were not reached, although the radiation monitors showed an increasing trend.

In another event, irradiated material was processed inside multiple hot cells. In the following days, the hot cells were opened by different workers, but not used. The workers assumed there was no contamination as they did not use the hot cells. When leaving the facility, the whole body contamination monitor displayed an error. The workers did not use another monitor at that time. Two days later, a different portal monitor was used, and it alarmed for contamination. Multiple workers and areas were determined to be contaminated.

4.8.2. Safety significance

All of the events discussed in Section 4.8.1 caused avoidable radiation exposure to personnel.. Although none of the events resulted in an exposure above the established dose limits, some of the events had the potential to do so.

4.8.3. Lessons learned

The events reported to the IRSRR in this category showed the need to:

- Ensure that all staff adhere to radiation protection procedures [18];
- Ensure that radiation detection devices are operable;
- Ensure that workers are trained to perform the task;
- Improve conduct of radiation monitoring and control on movement of radioactive material within different radiation and contamination areas.

4.9. EXPERIENCE WITH EXTERNAL HAZARDS

4.9.1. Summary of the root causes

External hazards such as earthquakes, storms, tsunamis, floods, lightning, extensive fouling of water intakes, and unusual weather conditions, as well as other external events such as loss of off-site electrical power supply, can be challenging for the safety of research reactors. Extreme conditions might develop beyond the design basis of the facility. The serious consequences of the accident at the Fukushima Daiichi nuclear power plant highlighted the importance of careful consideration and assessment of external hazards [19, 20].

A single earthquake event was reported to the IRSRR. A research reactor was in shutdown state when a 57-second-long earthquake occurred with intensity of 5.7 on the Richter scale. The safe shutdown condition was assured. The earthquake did not have any safety significant impact on the reactor. However, some parts of the walls of the reactor building cracked.

In an event of a volcanic eruption in the vicinity of the research reactor, volcanic ash was blown by the wind towards the research reactor. The two cooling towers, the piping system outside the reactor building, and the reactor dome were consequently covered by volcanic ash. Efforts were made to prevent the volcanic ash from affecting reactor safety by covering the reactor deck and bulk shielding with plastic sheets, cleaning up the SSCs in the reactor hall, filters, and blowers of the ventilation system.

Several events involving the loss of off-site electrical power supply were reported to the IRSRR. Problems with local power transformers or disturbances in the power grid resulted in reactor scrams. A reactor reported six reactor scrams within a year due to the low voltage in the electrical power supply. Each time the reactor was safely shutdown according to the design and without other implications. Another loss of electrical power supply, causing a reactor scram, was reported due to malfunction of a power transformer supplying power to the reactor site.

4.9.2. Safety significance

The earthquake event shows the importance of adequate assessment of the external hazards. Although the reactor was in shutdown state during the event, its safe condition was confirmed three days after the event. A detailed investigation was subsequently performed on the reactor SSCs to identify the impact of the earthquake. The reactor core, fuel elements, platform and reflector were not affected by the earthquake. However, several cracks were identified in the structure of the reactor building with the need for urgent renovation.

Volcanic eruptions in the vicinity of the reactor followed by spread of volcanic ash cause disruption in operation, choking of filters, and impact SSCs outside the reactor building, which may impact the performance of SSCs important to safety.

4.9.3. Lessons learned

Compared to other events, the IRSRR database contains a small number of events associated with external hazards. However, the reported events indicate that external hazards affect research reactors in various ways. The loss of off-site electrical power supply was shown to be a challenge for the reactor safety system in the reported incidents but had no important safety consequences for the reactor and environment.

Despite limited operating experience in relation to external hazards, the following lessons can be learned to improve research reactor safety:

- The robustness of the reactor SSCs to withstand external events and to assure basic safety functions has to be reassessed in accordance with the current standards;
- The emergency preparedness procedure has to consider the widespread aspects of external events involving earthquake and other possible external events and it has to include appropriate training of the staff;
- The actuation of reactor protection system using input from seismic signal has to be considered;
- The design and siting of research reactors have to take into account external hazards such as volcanoes in the vicinity of the research reactor.

In addition, most of the lessons learned from the accident at the Fukushima Daiichi nuclear power plant apply also to research reactors (see Annex II of this publication for additional discussions).

5. CONCLUSIONS

The main conclusions drawn from the analysis of the events reported to the IRSRR are as follows:

The IAEA's Incident Reporting System for Research Reactors (IRSRR) is an important tool for collecting and sharing the research reactor operating experience. Over the years, the IRSRR has grown from a source of reported events to a system to analyse the events, and to disseminate the lessons learned and corrective actions implemented among the presently 62 participating Member States. The analysis of these events also clearly illustrates that many events could have been avoided if the learning from similar events was applied. In some cases, similar events have recurred in the same facility indicating ineffective mechanisms for operating experience feedback. Sharing operating experience nationally and internationally will help operating organizations in taking preventive measures to reduce the frequencies and consequences of the events. The effectiveness of the IRSRR depends on the participation of its members through the timely submission of events at their research reactors.

Notwithstanding the variation in terms of design, type, power level and utilization of research reactors, many research reactor events bear similar causal analyses outcomes and lessons that, if used appropriately, can assist other operating organizations in preventing similar events.

Design and quality assurance

The events where design and quality assurance deficiencies were identified as the root cause highlighted the need for adequate design reviews and appropriate management system controls, including procedural controls for modifications and experimental devices. Some design deficiencies can remain latent and may go unnoticed for long periods of time, and then are finally revealed through an event. Several events related to fuel performance were attributed to design deficiencies and inadequate quality assurance. Design deficiencies in control and shim rods have resulted in rods failing to insert into the reactor on demand. Inappropriate material selection was one of the reasons for some events; these events show that inadequate care was taken while selecting the material for the service conditions of the components, resulting in failures and, in some cases, significant consequences. Deficiencies in the layout of components of the primary cooling system were identified as one of the causes for these events.

Some events revealed an ineffective implementation of quality assurance programmes during the construction and commissioning phases of research reactors. A significant number of the events indicated that design deficiencies had existed for a long period of time or even since the facility was first licensed. Effective maintenance and monitoring programmes are important in the identification of these hidden deficiencies. Adequate safety assessment of design and modification of SSCs need to be emphasized to ensure safety. In a few cases, a modification was implemented to improve the safety, however, new risks were introduced which were not analysed in the modification process resulting in an event. The integrated management system has to include a robust process for change management. This process has to cover all stages of the projects with safety significance.

Human factors

A large number of events have been reported where human factors and ineffective management of safety have either initiated the event or escalated it. Operating experience shows that most of these events can be attributed to organizational deficiencies, and corrective actions contribute to the development of a strong safety culture. The underlying causes of many events showed shortfalls in human performance involving all levels of the organizations and that included: inadequate recognition of risk or risk assessment, organizational and leadership shortfalls allowing weaknesses to be unrecognized or uncorrected, insufficient understanding or anticipation of the safety consequences of human actions, gradual decline in standards and performance that went unnoticed and evolved into a significant drop in standards, lack of supervision, shortfalls in competencies, tolerance of problems with equipment or personnel, insufficient engagement of all those involved in decision making, and ineffective use of operating experience to learn lessons and prevent the events. A questioning attitude has to be encouraged at all levels of staff at the facility; however, social hierarchy and cultural aspects sometimes can make this difficult to achieve. Many of the events reported to the IRSRR may have been avoided if operating personnel had questioned the prevailing practices.

Most of the events in this category show that the events could have been prevented if the personnel involved had followed the procedures, and if the availability of these procedures and their implementation were ensured. In several instances, the risk was not accurately perceived. The events show that many actions were performed without realizing the potential consequences associated with them. The reactor management has to ensure that the personnel (operators, contractors, students, visitors, experimenters) engaged at different levels than managers or supervisors do understand the significance of their actions and their effects on safety. It is vital that events with potential safety implications are adequately identified and investigated, and their root causes and contributing factors are clearly determined. Not determining the actual root causes and contributing causes can lead to potential latent organizational weakness that may lead to treatment of the symptoms instead of the problems.

An adequate management system is an effective measure in event prevention. A strong safety culture is essential for ensuring that the management system is followed at all levels in the operating organization. A strong questioning and learning attitude of operating personnel is an aspect of safety culture that ensures benefits are derived from operating experience.

Maintenance and ageing

The experience from the IRSRR indicates that many of the research reactors are challenged by the negative impacts of ageing of SSCs. Although maintenance is one of the elements of an ageing management programme, many ageing effects cannot be addressed in a routine maintenance programme and may require special attention in the form of a refurbishment project. Additionally, the effects of ageing need to be evaluated for impacts to the design bases of SSCs important to safety. Undetected corrosion of pipes, valves, and tanks, and leaks resulting from these were reported in a number of events. Some of these events have taken place in inaccessible parts such as buried pipes, entombed tanks, and reactor vessels. Fatigue cracking and radiation damage of the components are other important contributors to the events related to ageing in research reactors. The events in this category also show that most of the components affected have been the mechanical components, with few events concerning electrical systems and I&C systems. These events highlighted the need for establishing in a timely manner an effective ageing management programme that integrates maintenance, periodic testing and inspection. The ageing management programme has to identify all relevant degradation mechanisms and provisions to detect, monitor and trend ageing effects of SSCs in order to implement suitable minimization and mitigation measures.

Experimental devices, which are specific to research reactors, have been associated with several events caused by ageing degradation and, thus, need adequate attention. The analysis of the events reported to the IRSRR indicates that the consequences of some events could have been worse if the conditions were different or the corrective actions were delayed. The need for proper training of maintenance personnel when new technology is introduced to a facility is evident in event and the need for their comprehensive understanding, not only of the new technology, but also of its impact on the safety of the facility.

Reactivity control

The events in this category reported the most severe consequences including core damage, high radiation exposure to operating personnel, injuries to the operating personnel, and severe contamination within the reactor facility. These are the only events reported to the IRSRR for which deaths of operating personnel have occurred. Events related to inadvertent reactivity additions reported to the IRSRR indicate that these are independent of the type or power of the reactor. The important lesson learned from these events is that research reactors are vulnerable to reactivity related events mainly due to the frequent fuel handling and direct interaction with the reactor core, including experiments. The consequences of reactivity insertion events are often severe and can be limited only by the built-in safety features and administrative procedures. Nuclear criticality accidents occur rapidly without any preceding warning and manual intervention is often not possible. Any activity which has a potential effect on core reactivity has to be adequately reviewed before its implementation. According to the events reported to the IRSRR, many events could have been avoided if the operating personnel had reviewed their actions before implementing them. In some of the reported events, the procedures were not followed, and the operating personnel used their own discretion, thereby jeopardising the safety of the reactor and of the operating personnel. The events also highlight the importance of a second independent shutdown system.

Utilization and modifications

During the lifetime of a research reactor, new experiments are introduced, and the reactor facilities are modified based on the changes in the utilization programme. Several events related to material irradiation were reported to the IRSRR, including the failure of target containers, irradiation of targets at different reactor power or irradiation positions, and the mishandling of the irradiation capsules and devices. Additionally, the events have shown that modifications to the experiments and experimental devices that are not subject to a structured process can result in loss of configuration controls or design changes that may lead to radiological consequences. The events indicate that experiments or irradiations of new targets have to be subjected to an adequate safety analysis covering the design, construction and operation of irradiation and experimental devices. The potential consequences have to be evaluated, and measures have to be defined and implemented before the conduct of experiments or irradiation. Radiation exposure to operating personnel and contamination of the areas can be minimized by following the approved operating procedures covering the safety aspects of the experiments and irradiation activities.

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[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Reassessment for Research Reactors in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, Safety Reports Series No. 80, IAEA, Vienna (2014).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience 2015–2017, IAEA, Vienna (2020).

ANNEX I: INSIGHTS ON RESEARCH REACTOR EVENTS FROM SOURCES OTHER THAN IRSRR

I–1. A REVIEW OF CRITICALITY ACCIDENTS, 2000 REVISION, LOS ALAMOS NATIONAL LABORATORY, LA-13638

This publication discusses 60 criticality accidents that occurred since the early years of nuclear technology. Out of these, 33 accidents occurred at critical facilities, and 5 at other research reactor facilities. All these reactor accidents happened during shutdown, startup or low power operation. Some of these events are also mentioned in the IRSRR database. The 38 accidents in research reactors resulted in 12 fatalities. In 10 cases, the installation was severely damaged. This overview indicates that criticality accidents are the worst possible accidents with research reactors. Compared to NPPs, many more manipulations are performed, often with highly reactive fuel elements that can be the source of significant reactivity introduction in the core.

I–2. DAVID MOSEY, REACTOR ACCIDENTS, INSTITUTIONAL FAILURE IN THE NUCLEAR INDUSTRY, SECOND EDITION, NUCLEAR ENGINEERING SPECIAL PUBLICATIONS, 2006

This publication discusses seven well known reactor accidents with a lot of attention given to the human factors aspect and deficiencies in organizational matters, which are, in many of the cases, the root causes of the accidents. Two of these accidents are also included in the IRSRR database. The first is the accident at the NRX reactor (Ontario, Canada, December 1952). This accident is considered to be the first reactor accident that occurred. Previous accidents took place in critical facilities or fuel processing installations. The second event is the accident at the SL-1 reactor (Idaho, USA, January 1961).

The Windscale accident (Cumbria, UK, October 1957) that is not included in the IRSRR database is of particular interest to the research reactor community. The reactor was graphite moderated, air cooled and natural uranium metal fuelled reactor. In order to release the Wigner (stored) energy of graphite, the annealing operation was routinely performed in the reactor by raising the temperature of the core in a controlled manner by manipulating reactor power and coolant air flow (this operation raises the temperature of the graphite that aids in releasing the Wigner energy). During the event, the operators misjudged the rate of temperature rise and overheated the core by a combination of low air flow and high reactor power. The fuel caught fire and the entire reactor was destroyed. Substantial activity was released into the atmosphere.

Information about the other accidents in the publication is also useful for research reactors.

I–3. T.J. THOMPSON AND J.G. BECKERLEY (EDS), THE TECHNOLOGY OF NUCLEAR REACTOR SAFETY, MIT PRESS, 1964

Chapter 11 (accidents and destructive tests) of this book contains an overview of all nuclear incidents up to 1964. A number of them are described in detail, with a discussion on the causes of the incident. One of these accidents, which is of particular interest to the research reactor community and which was not reported to the IRSRR, is briefly described below.

The EBR-I meltdown (Idaho, USA, November 1955)

The experimental breeder reactor was a NaK cooled fast spectrum reactor with a thermal power of 1400 kW. Measurements at low power were performed to obtain more information on reactivity coefficients. During earlier experiments, it was observed that the power coefficient of reactivity had a large positive component. The purpose of the tests was to obtain more information on its origin. During one of the tests, the power increased more rapidly than expected and could not be controlled due to slow response of the control system instrumentation. The test resulted in an estimated power peak of about 9000 kW, when the control rods dropped. The total energy release was calculated to be 14 MJ. The core was destroyed. Contamination remained limited due to the low burnup of the fuel (0.1%).

The EBR-I accident demonstrated that experiments have to be carefully prepared. Safety systems have to be available that can interrupt the experiment rapidly in case of severe deviations. Preferably, these systems have to be independent from the experiment.

ANNEX II: OPERATING EXPERIENCE FEEDBACK OF NUCLEAR POWER PLANTS FROM THE INTERNATIONAL REPORTING SYSTEM FOR OPERATING EXPERIENCE RELEVANT TO RESEARCH REACTORS

The database of the IRSRR is an important source of information about the reported events that have occurred at research reactors globally. However, other sources are available which also contain useful information. The overview report from the IAEA and OECD/NEA International Reporting System for Operating Experience (IRS), which deals with events in NPPs, contains a number of lessons learned (see Ref. [II–1]). The research reactor community can benefit by learning from the lessons that are applicable to research reactors.

The important lessons learned from events at NPPs that are relevant to research reactors are summarized below:

- Understanding of the design basis and retaining accurate and complete documentation from commissioning of the facility onwards is important. This is particularly important as most research reactors were constructed and commissioned many years ago. The documentation from that time is usually limited, and the original designers, installation and commissioning engineers and operating personnel are no longer available. For the older research reactors, an effort to recuperate as much information as possible is useful such that the design bases could be reconstituted as completely as possible.
- Beside the formal equipment surveillance programmes or logging of indications as prescribed by regulations and/or technical guidance, it is also important to have good engineering and operations practices such as questioning attitudes, recognition of off-normal indications and thoughtful consideration of the impact of adverse equipment conditions on the overall facility.
- Attention has to be paid to possible undetected equipment failures that could exist for a long time. Another single failure can then result in an event with serious consequences. A comparable remark is valid for multiple human errors where a faulty response to an event can make the situation even more complex.
- Before a task is started, an estimation of the radiological aspects is necessary, not only for the normal situation but also for anticipated failures of equipment or possible human errors.
- When components, especially those related to the safety systems of the facility, are replaced by equivalent components, close attention has to be paid to ensure that at least the same level of safety is kept. In many cases, identical replacement parts will not be available and a modification is necessary. The modification has to be assessed according to its safety category.
- An effective communication within the organization, through all levels and across organizational boundaries is vital for the safety of the facility. All involved parties have to be aware of and recognize the potential impact of their activities on others. Organizations have to look outside their own boundaries to see who else may be impacted, or who may be impacting them. The continuously changing environment in today’s nuclear industry requires added diligence to ensure that communication is clear, concise and complete.
- A lack of sharing of information on operating experience is one of the major contributors to some events. If previous similar events had been recognized throughout the research reactor community, their recurrence might have been avoided. These events imply that it is important to disseminate information on operating experience and incorporate the appropriate corrective actions based on the lessons learned.

A severe accident occurred in March 2011 at the Fukushima Daiichi nuclear power plant in Japan following a severe offshore earthquake and subsequent tsunami. Flooding of the power plant and damage to equipment due to the tsunami resulted in an extended station blackout, loss of core cooling, fuel melting, hydrogen explosions and releases of radioactive material to the surrounding region, with significant contamination of the environment. The available experience from this accident is useful for defining and implementing measures to prevent the occurrence of any accident involving a large release of radioactive material at nuclear installations, including at a research reactor, in the future.

The majority of research reactors were built to earlier safety standards, which are not fully consistent with the current IAEA safety standards and which do not include the defence in depth concept. In particular, for many research reactors the design of SSCs important to safety is not in accordance with the criterion for common cause failure (i.e. the ability to withstand the failure of two or more structures, systems or components due to a single specific event or cause), and the confinement or containment buildings of several research reactors located near populated areas have deficiencies in their leak tightness. In addition, the safety analyses for many research reactors have not been updated to take into account modifications of the facilities and changes in the characteristics of their sites and site vicinity areas. These elements and the feedback from the accident at the Fukushima Daiichi nuclear power plant justify a revision of the safety analysis for these facilities through the performance of a safety reassessment.

The IAEA has published Safety Reports Series No. 80, Safety Reassessment of Research Reactors in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [II–2]. This publication provides information relevant for all steps in performing such safety reassessments for research reactors and their associated facilities, such as experimental facilities and devices, and radioisotope production facilities. Although it primarily focuses on operating research reactors, the approaches and methods described in this publication also apply to research reactors that are in the design or construction phases, or in an extended shutdown state.

The safety reassessment as described in Ref. [II–2] includes a review of the design basis accidents and design extension conditions of the research reactor facility and its site, as well as a reassessment of arrangements for preparedness for, and response to, an emergency resulting from such accidents. It also provides information on the application of a graded approach and suggested processes for the implementation of the findings of the safety reassessment.

REFERENCES TO ANNEX II

[II–1] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience 2015–2017, IAEA, Vienna (2020).

[II–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Reassessment for Research Reactors in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, Safety Reports Series No. 80, IAEA, Vienna (2014)

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ANNEX III: OPERATING EXPERIENCE PROGRAMME DESCRIPTION

III-1 GENERAL

Operating experience is a valuable source of information for learning and for the process of improving the safety and reliability of research reactors.

IAEA Safety Standards Series No. SSR-3, Safety of Research Reactors [III–1], establishes requirement 88 on the feedback of operating experience and requires “the operating organization for a research reactor facility shall establish a programme to learn from events at the reactor facility and events in other research reactors and from nuclear industry” Additional requirements are provided in para 7.126-7.129 of SSR-3 [III-1]. IAEA Safety Standards Series No. SSG-50, Operating Experience Feedback for Nuclear Installations [III–2], provides detailed guidance in this regard.

The primary objectives of a system for the feedback of operating experience are that no safety related event remains undetected and that corrections are made to prevent the recurrence of safety related events by improving the design and/or the operation of the installation. This criterion reflects the notion that an accident of any severity would most probably have been marked by precursor events, and to this extent would have been predictable and, therefore, avoidable. Feedback of experience also increases knowledge of the operating characteristics of equipment and performance trends, and provides data for quantitative and qualitative safety analysis.

The operating organization has a responsibility to ensure that operating experience is used effectively within the organization to promote safety. Therefore, it is important for the operating organization to have an effective programme for identifying, analysing and reporting events in order to feedback the lessons learned.

An effective operating experience programme relies on certain essential characteristics, including that:

- Policies are established by the management of the operating organization, to align the organization to effectively implement the operating experience programme. These policies include established thresholds and criteria set for expectations and priorities;
- Event identification and reporting is strongly encouraged at all levels in the organization;
- Timely identification and reporting of events are undertaken to ensure that the facts are communicated and recorded properly so that learning opportunities can be extracted and followed through;
- Collection of information is timely and sufficiently comprehensive so that no relevant data is lost;
- The information collected is screened effectively by knowledgeable persons, to ensure that all important safety related issues that have to be reported and analysed with priority are identified;
- Employees who identify problems receive feedback on problem resolution;
- Appropriate resources (personnel, equipment, funds) are allocated by the management of the operating organization to support the operating experience programme;
- Management of the operating experience programme is focused on improvement of safety;

- Facility personnel at all levels of the organization demonstrate ownership for identifying, reporting and screening of events by directing, promoting, prioritizing, and sufficiently staffing programme activities;
- Failures and near misses are considered opportunities to learn and are used to avoid more serious events;
- Management of the operating organization provides continuous direction and oversight.

III-2 EVENT IDENTIFICATION

The first key activity of the operating experience programme is to identify events or good practices. The purpose of identifying events is to feed the operating experience programme with information for further evaluation, and corrective actions to reduce potential for event recurrence, and the applicability of good practices.

In the context of the operating experience programme, an event is any occurrence unintended by the operator, including operating error, equipment failure or other mishap, and deliberate action on the part of others, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.

Identifying events has to include the capability of personnel to recognize deficiencies, or potential or actual adverse conditions, and provide suggestions for improvements, as well as the capability to recognize good practices.

Management has to establish and communicate the expectations on the threshold for identifying events. Experience has shown that causes of low level events and near misses can be similar as causes of significant events.

All events, however minor, present learning opportunities to improve safety and performance, reduce errors and avoid repeat issues. Good practices, either external or internal, are also opportunities to emulate for improving safety and performance. Identifying activities are focused on what is wrong (the gap or deviation between ‘what is’ and ‘what should be’) and what needs to be improved.

III-3 MAIN ELEMENTS OF AN OPERATING EXPERIENCE PROGRAMME

The main elements of an effective operating experience programme are:

- Reporting of events;
- Screening of events – based on safety significance;
- Investigation of events;
- Causal analysis;
- Recommended actions resulting from the assessment, including approval, implementation, tracking and evaluation;
- Trend evaluation;
- Dissemination and exchange of information including by the use of international systems such as IRSRR;
- Continuous monitoring and improvement of programmes for the feedback of operating experience;
- Documentation.

A detailed procedure has to be developed by the operating organization on the basis of the requirements for a national system established by the regulatory body. This procedure has to define the process for dealing with all internal and external information on events at research reactors. The procedure has to define the structure of the system for the feedback of operating experience, the types of information, the channels of communication, the responsibilities of the groups and organizations involved, and the purpose of the documentation produced.

Screening of event information is undertaken to ensure that all significant matters relevant to safety are considered and that all applicable lessons learned are taken into account. The screening process has to be used to select events for detailed investigation and analysis. This includes prioritization according to safety significance and the identification of adverse trends.

The use of external operating experience can have the benefit of discovering latent potential failures that could pose concerns for safety. Such information has to be reviewed to determine whether it is applicable to the facility and if any actions are warranted.

The level and scope of the investigation to be carried out has to be commensurate with the consequences of an event and the frequency of recurring events using a graded approach (see also IAEA Safety Standards Series No. SSG-22 (Rev. 1), Use of a Graded Approach in the Application of the Safety Requirements for Research Reactors [III–3]).

Event analysis has to be conducted on a timescale consistent with the safety significance of the event. The main phases of event analysis can be summarized as follows:

- Establishment of the complete event sequence (what happened);
- Determination of the deviations (how it happened);
- Cause analysis;
- Direct cause (why it happened);
- Root cause (why it was possible);
- Assessment of the safety significance (what could have happened);
- Identification of corrective actions.

Actions taken in response to events constitute the main basis of the process of feedback of operating experience to enhance safety at nuclear installations. Such actions are aimed generally at correcting a situation, preventing a recurrence, or enhancing safety.

The development of recommended corrective actions following an event investigation has to be directed towards the root causes and the contributory causes and has to be aimed at strengthening the weakened or breached barriers that failed to prevent the event.

A tracking process has to be implemented to ensure that all approved corrective actions are completed in a timely manner and that those actions with long lead times to completion remain valid at the time of their implementation in the light of later experience or more recent developments.

The purpose of an event trending process has to be to determine the frequency of occurrence of certain conditions that have been gathered from reports on minor and major problems and event investigations. These data include information about equipment failures and shortfalls in human performance, and situational data that describe conditions at the times of the events.

Once an abnormal trend has been identified it has to be treated as an event, and the established deficiency reporting programme is used to initiate an appropriate analysis and to determine whether the trend is identifying adverse performance.

For maximum impact and benefit, appropriate information relating to the feedback of operating experience has to be disseminated to relevant bodies. A list of possible recipients for different types of information has to be prepared. A periodic review has to be undertaken of all stages of the process for the feedback of operating experience, to ensure that all of its elements are performed effectively. Continuous improvement of the process for the feedback of experience is an objective of the review.

The operating organization or licensee has to be responsible for integrating operating experience feedback into its management system in accordance with national and international standards.

The event reporting has to be established in accordance with the licensing conditions and OLCs of the facility. The event reporting system includes the reporting criteria, format of the report, timeline for reporting and the individuals and/or organization to which the report is submitted. IRSRR guide is a useful publication in developing the event reporting system.

Generally, the event report includes:

- Basic information;
- Narrative description;
- Safety assessment (consequences and implications);
- Causes and corrective actions (taken and/or planned);
- Lessons learned;
- Graphic information (e.g. drawings, sketches, photos, process and instrumentation diagrams) for a better understanding of the event (if necessary).

Basic information includes items such as: title of the event; date and time of occurrence; facility name, site; facility type and rated power output; facility status at the time of event (operation, maintenance, refuelling, startup, shutdown); and an abstract containing a brief statement describing the major occurrences during the event, including all actual component or system faults and failures that contributed to it, all relevant personnel actions or violations of procedures and any significant corrective action taken or planned as a result of the event.

The narrative description explains exactly what has happened and what has been discovered in the event. Emphasis is put on how the facility responded and how structures, systems, components, and operating personnel, performed. A description of what the operator observed, did, understood or misunderstood is important, including how the event was discovered. Unique characteristics of the facility which influenced the event (favourably or unfavourably) are described. The following specific information is included: facility status prior to and following the event; event sequence in chronological order; system and component faults; operator actions and procedural controls; and recurrent events.

The safety assessment has to be focused on the safety consequences and implications of the event. The primary aim of this review is to ascertain why the event occurred and whether it would have been more severe under reasonable and credible alternative conditions, such as at different power levels or in different operating modes. The safety significance of the event has to be indicated.

The direct, root causes and causal factors of the event have to be clearly described. The causes have to include reasons for equipment malfunctions, human performance problems, organizational weaknesses, design and manufacturing deficiencies and other facts. The cause analysis has to be conducted by trained personnel.

All corrective actions taken or planned have to be listed and described in sufficient detail. In case of a number of planned corrective actions, they have to be clearly prioritized. For follow-up purpose, the individuals, group, or department responsible for authorizing or implementing corrective action may be identified.

The report has to clearly identify the lessons learned from the event. The communication of lessons learned can lead to enhanced safety, positive changes in working practices, increased reliability of equipment and improvements in procedures. The sharing of lessons learned from operating experience is one of the most valuable parts of the process of feedback of operating experience.

The event report has to be shared at national level through established channels and at international level using established systems such as the IRSRR.

REFERENCES TO ANNEX III

[III–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Research Reactors, IAEA Safety Standards Series No. SSR-3, IAEA, Vienna (2016).

[III–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Operating Experience Feedback for Nuclear Installations, IAEA Safety Standards Series No. SSG-50, IAEA, Vienna (2018).

[III–3] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of a Graded Approach in the Application of the Safety Requirements for Research Reactors, IAEA Safety Standards Series No. SSG-22 (Rev. 1), IAEA, Vienna (2023).

ABBREVIATIONS

EBR-1	Experimental Breeder Reactor-1
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
INES	International Nuclear and Radiological Event Scale
IRS	International Reporting System for Operating Experience
IRSRR	Incident Reporting System for Research Reactors
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRX	National Research Experimental
OLCs	Operational Limits and Conditions
SL-1	Stationary Low-Power Reactor Number One
SSCs	Structures, Systems, and Components
TRIGA	Training, Research, Isotopes, General Atomics

CONTRIBUTORS TO DRAFTING AND REVIEW

D'Arcy, A.	South African Nuclear Energy Corporation, South Africa
Gavello, M.	US Nuclear Regulatory Commission, United States of America
Hardesty, D.	US Nuclear Regulatory Commission, United States of America
Hargitai, T.	International Atomic Energy Agency
Joppen, F.	Federal Agency for Nuclear Control, Belgium
Laine, N.	International Atomic Energy Agency
Juhasz, L.	Hungarian Atomic Energy Authority, Hungary
Lolich, J.	International Atomic Energy Agency
Naseer, F.	International Atomic Energy Agency
McIvor, A.	Consultant, Canada
Mottl, V.	Australian Radiation Protection and Nuclear Safety Agency, Australia
Rao, D.	Consultant, India
Shokr, A. M.	International Atomic Energy Agency
Usman, M.	Pakistan Nuclear Regulatory Authority, Pakistan
Waddel, T.	Consultant, United States of America

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