IAEA-TECDOC-1762

IAEA TECDOC SERIES

IAEA-TECDOC-1762

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

IAEA

International Atomic Energy Agency

IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available at the IAEA Internet site

http://www-ns.iaea.org/standards/

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety and protection in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

The **IAEA Nuclear Energy Series** consists of reports designed to encourage and assist research on, and development and practical application of, nuclear energy for peaceful uses. The information is presented in guides, reports on the status of technology and advances, and best practices for peaceful uses of nuclear energy. The series complements the IAEA's safety standards, and provides detailed guidance, experience, good practices and examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

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

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA, ISLAMIC REPUBLIC OF
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA-TECDOC-1762

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

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2015

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

Printed by the IAEA in Austria
March 2015

IAEA Library Cataloguing in Publication Data

Operating experience from events reported to the IAEA
Incident Reporting System for Research Reactors.
— Vienna : International Atomic Energy Agency, 2015.
p. ; 30 cm. — (IAEA-TECDOC series, ISSN 1011–4289
; no. 1762)
ISBN 978–92–0–100615–8
Includes bibliographical references.

1. Nuclear reactors — Safety measures — International cooperation. 2. Nuclear reactors — Safety regulations. 3. Nuclear reactor accidents. I. International Atomic Energy Agency. II. Series.

IAEAL 15–00957

FOREWORD

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

The Incident Reporting System for Research Reactors (IRSRR), which is operated by the IAEA, is an important tool for international exchange of operating experience feedback for research reactors. The IRSRR reports contain information on events of safety significance with their root causes and lessons learned which help in reducing the occurrence of similar events at research reactors. To improve the effectiveness of the system, it is essential that national organizations demonstrate an appropriate interest for the timely reporting of events important to safety and share the information in the IRSRR database.

At their biennial technical meetings, the IRSRR national coordinators recommended collecting the operating experience from the events reported to the IRSRR and disseminating it in an IAEA publication. This publication highlights the root causes, safety significance, lessons learned, corrective actions and the causal factors for the events reported to the IRSRR up to September 2014. The publication also contains relevant summary information on research reactor events from sources other than the 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.

This publication will be of use to research reactor operating organizations, regulators and 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 D. Rao and A.M. Shokr of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Since 1997 the IAEA is operating the Incident Reporting System for Research Reactors (IRSRR). The information on the safety significant events occurring in research reactors are 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 on '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 take into account 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.

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 operating experience feedback from the events reported to the IRSRR including root cause(s), lessons learned, and corrective actions taken to prevent the occurrence of similar events in other reactors.

1.3. SCOPE

The publication covers the analysis of the reported events to the IRSRR up until September 2014 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 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 in the research reactors [3]. The publication is intended for use by research reactor operators, regulators, and designers.

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 during the last five years. Section 4 discusses the events reported to the IRSRR, including their root causes, safety significance, lessons learned and corrective actions established on the basis of these events. Section 5 provides a brief conclusion. The annexes provide, respectively, reference to other relevant publications, lessons learned from recent events at nuclear power plants 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 IRSRR?

Systematic collection and evaluation of operational 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.

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

Requirements on incident assessment and reporting are included in the IAEA Safety Standards NS-R-4 [4] which states that “It shall be the responsibility of the operating organization to ensure that information on reportable incidents, including any assessments of such events and the corrective actions intended, is submitted to the regulatory body”.

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;”, 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”.

2.2. BENEFITS OF IRSRR

Being 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 are benefitted through the exchange of information on the events, and the lessons learned and corrective actions taken by the operating organization. This heightens the awareness among the participating Member States to take advance actions for preventing similar events in their research reactors.

The participating Member States also use the IRSRR 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 IRSRR data is the application of operational feedback in the design of the 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 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 users 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 IRSRR, but which 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, sketches, etc. The national coordinator also identifies the categorization codes for the important aspects of the event as per the coded watch-list of the IRSRR guide, and assigns the report as ‘specific report’ or ‘generic report’.

2.3.2. Sharing information

IRSRR is a part of the web-based incident reporting common platform of the IAEA NUCLEUS portal [Fig.1]. The system allows access only to the authorised persons. The user manual has 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.

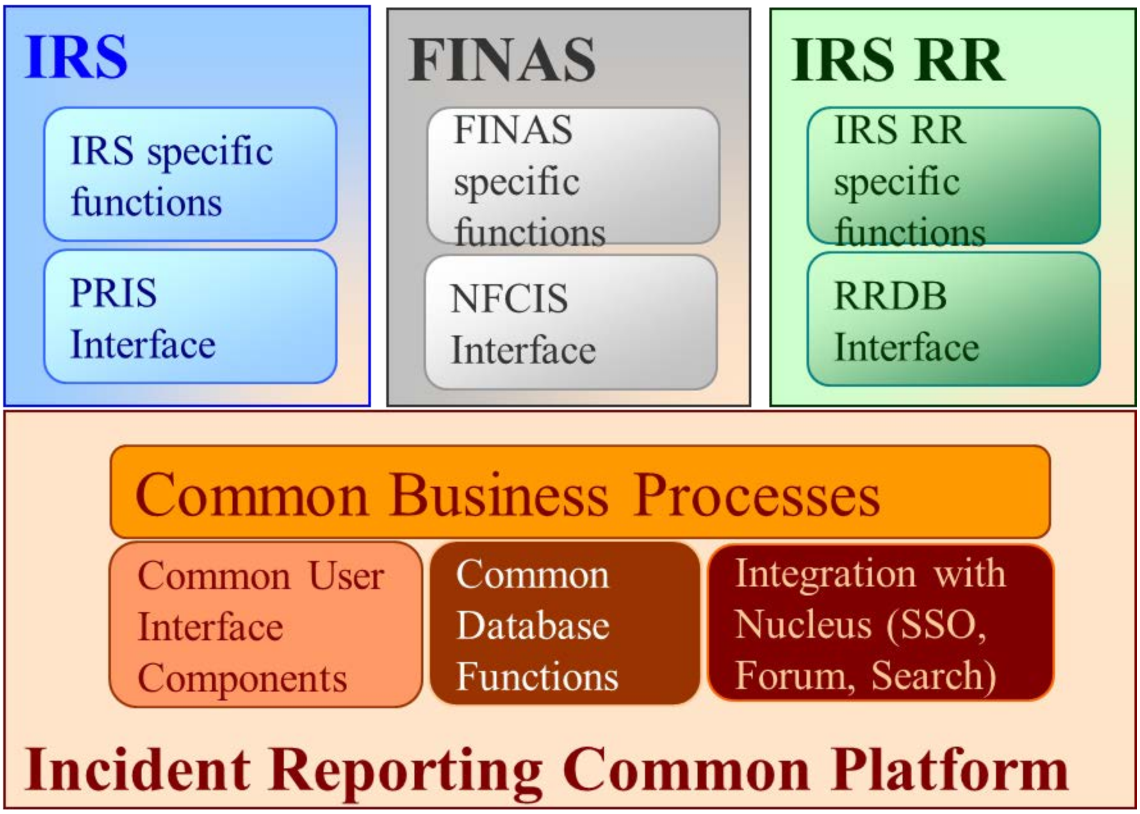

Fig.1. IAEA's incident reporting systems for nuclear installations.

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 IRSRR reports is restricted and is limited to the authorised 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 benefit from the exchange of the experience among the participating Member States.

2.4.3. Other activities

The IAEA and Nuclear Energy Agency (NEA) also jointly maintain the International Nuclear and Radiological Event Scale (INES). The INES was introduced in 1990 and its' primary purpose is to facilitate communications and understanding among the nuclear community, the media and the public, on the safety significance of events occurring at nuclear installations. It is expected that relevant research reactor events reported to INES are also reported to IRSRR.

2.5. WHAT HAS BEEN ACHIEVED?

Up until 2014, fifty six Member States with an interest in research reactors have been participating in the IRSRR (Table1.). However, the reporting of the events is rather limited. Until September 2014, there have been 186 event reports from 41 Member States in the IRSRR database. The oldest report being that from an event, that occurred in 1947 and the most recent being from September 2014. In order to maximize the benefits from IRSRR, it is necessary that the participating Member States submit the events that have an element of lesson to be learned, including precursors to events.

Over the years, IRSRR has developed from a source of information exchange on the events to becoming a source for analysis, detailed discussion on the events, refining the event investigation techniques and 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 that is taken into account when identifying the topical areas for planning IAEA activities on research reactor safety. By 2014, eight biennial technical meetings of the IRSRR national coordinators were held.

TABLE 1. PARTICIPATING MEMBER STATES IN IRSRR AS ON SEPTEMBER 2014

Argentina	France	Korea	Romania
Australia	Germany	Latvia	Russian Federation
Austria	Ghana	Libya	Serbia
Bangladesh	Greece	Malaysia	Slovenia
Belgium	Hungary	Mexico	South Africa
Brazil	Indonesia	Morocco	Sweden
Bulgaria	Iran	The Netherlands	Syria
Canada	Iraq	Nigeria	Thailand
Chile	Israel	Norway	Tunisia
China	Italy	Pakistan	Turkey
Czech Republic	Jamaica	Peru	Ukraine
DR of Congo	Japan	Philippines	United Kingdom
Egypt	Jordan	Poland	USA
Finland	Kazakhstan	Portugal	Vietnam

3. OVERVIEW OF THE EVENTS REPORTED TO IRSRR

The events reported to the IRSRR are characterized using a set of guidewords as defined in appendix II of the IRSRR guidelines [1]. There are nine groups of guidewords 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 guidewords are assigned numerical codes. The guidewords describe the typical systems, root causes, consequences, affected systems/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 to be noted that more than one guideword can be selected within each group. The IRSRR guidewords are a simplified means to search and retrieve the information on events. The events reported to the IRSRR in the last five years were analysed with the help of these guidewords and an overview of the analyses is presented below:

I. The reporting category of an event identifies the category into which an event falls as per the IRSRR guidelines. It is to be noted that an event may fall into more than one reporting category and hence some overlap is unavoidable.

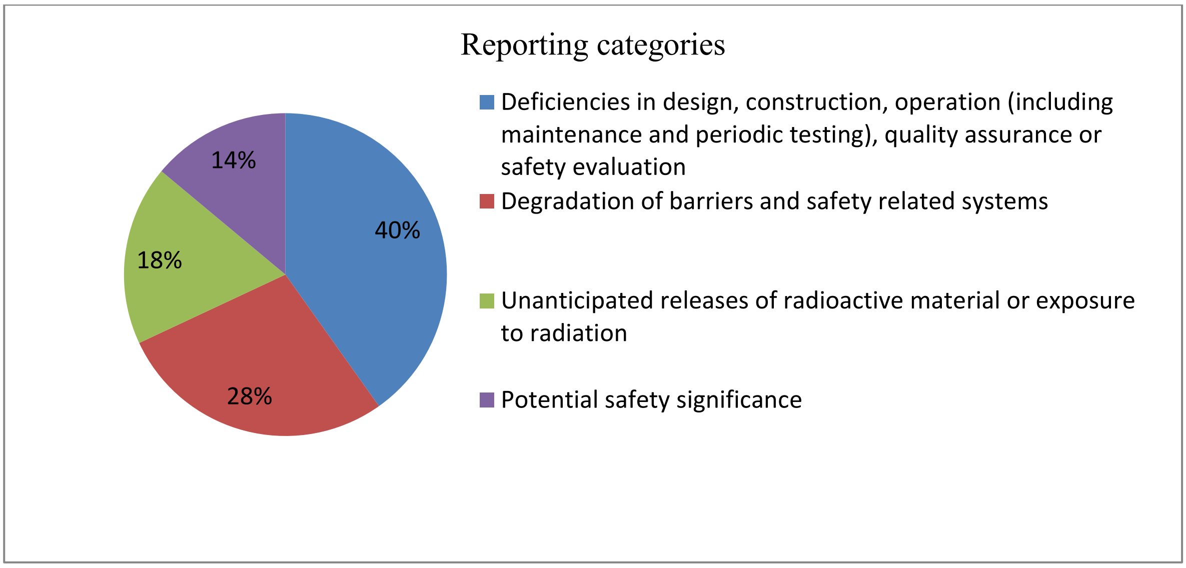

Fig.2. Distribution of the analysed events as per reporting categories.

Among the events analysed, the largest number of events (40%) 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)' (28%). About 18% of the events were reported in the category of 'unanticipated releases of radioactive material or exposure to radiation', and 14% of the events were reported in the category of 'potential safety significance (potential unsafe situation)'. Fig. 2 shows the distribution of events based on reporting category.

II. The analysis of the event reports showed the following grouping according to the characteristic of events: The largest number of events resulted in 'degradation or malfunction of experimental devices' (20%) followed by 'degradation of coolant boundary' (17%) and 'failure or significant degradation of reactivity control' (15%), ; the distribution of events that resulted in: 'degraded fuel' (7%), 'discovery of major condition not previously considered or analysed' (7%), 'transient' (6%), 'fuel handling' (6%), 'loss of safety function' (5%), 'degraded reactor containment/confinement' (4%), and 'significant degradation of safety function' (4%). The least number of events resulted in: 'failure or significant degradation of heat removal capability', 'loss of off-site power', 'physical hazards (internal or external to the facility)', 'radioactive waste incident', and 'security, safeguards, sabotage or tampering issues'. Fig. 3 shows the distribution of events as per the characteristics of the events.

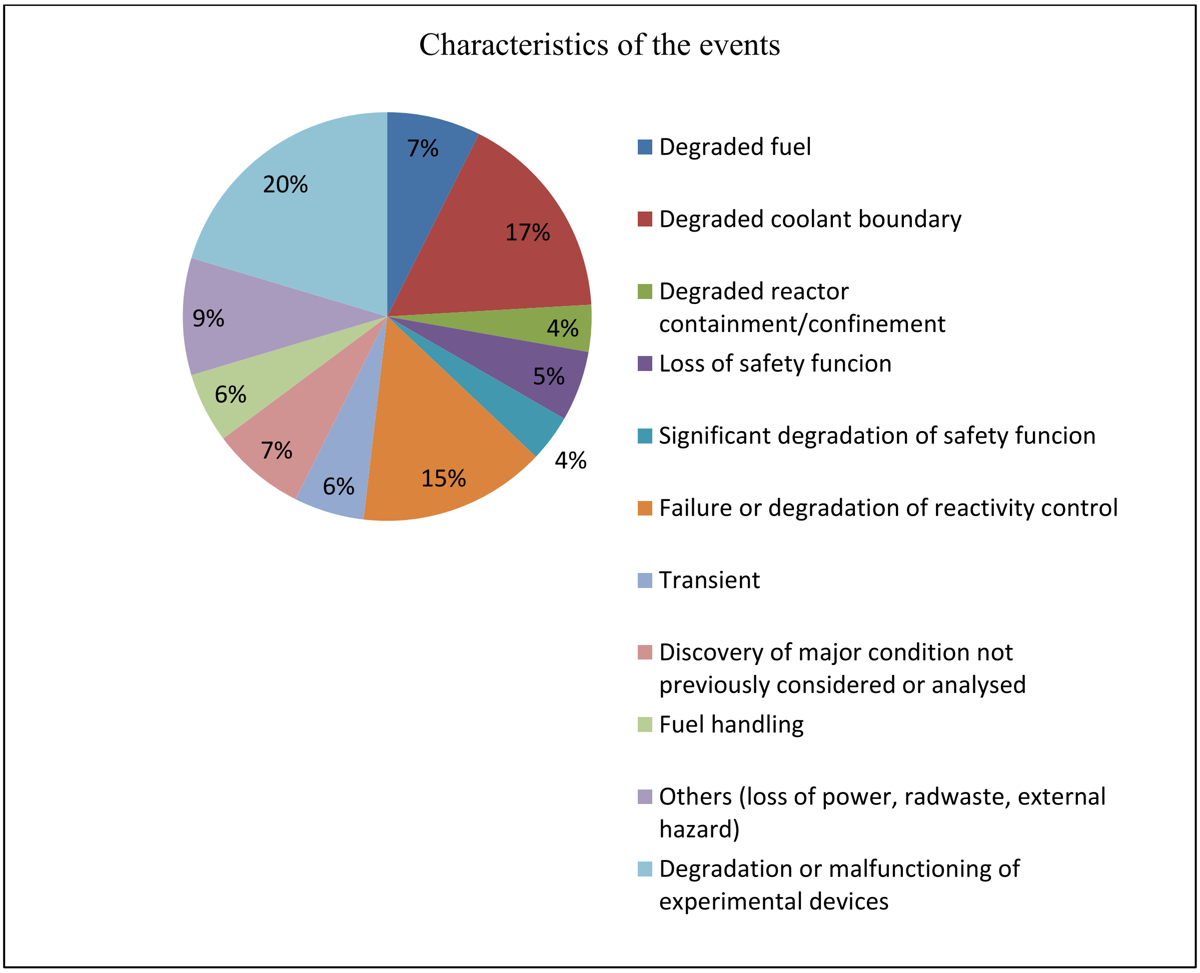

Fig.3. Distribution of the analysed events as per characteristics of the event.

III. The analysis of the events showed that 'mechanical components' (69%) were the most affected components of research reactors followed by 'instrumentation (gauges, transmitters, and sensors)' (24%). There are a few events (7%) related to 'electrical' components. Computer related failure was not reported. Fig. 4 shows the distribution of failed/affected components.

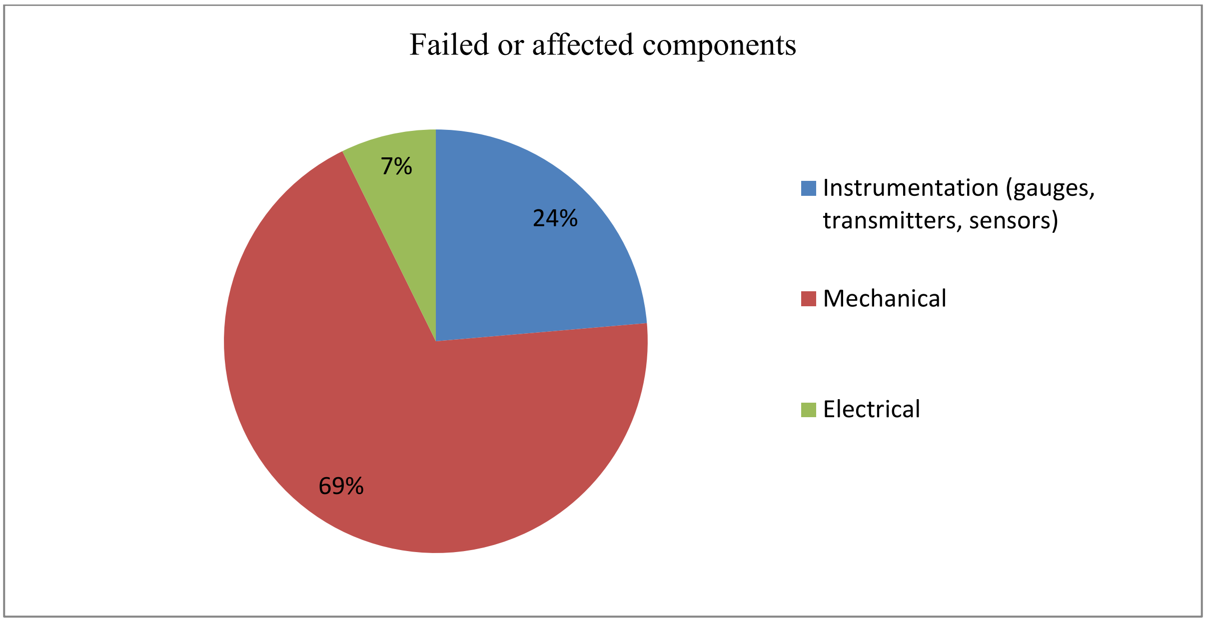

Fig.4. Distribution of the analysed events as per failed or affected components.

IV. The analysis of the causes of events showed that the 'human factors' (40%) is the leading root cause of events closely followed by the 'ageing of Systems, Structures and Components (SSCs)' (39%) which result in the failure of SSCs due to corrosion, fatigue, crack, vibration etc. Other main contributors to the cause of events were 'design and quality assurance' related events (11%), and the events where 'management of safety' was identified as the main cause (10%). Fig.5 shows the distribution of root causes for the analysed events.

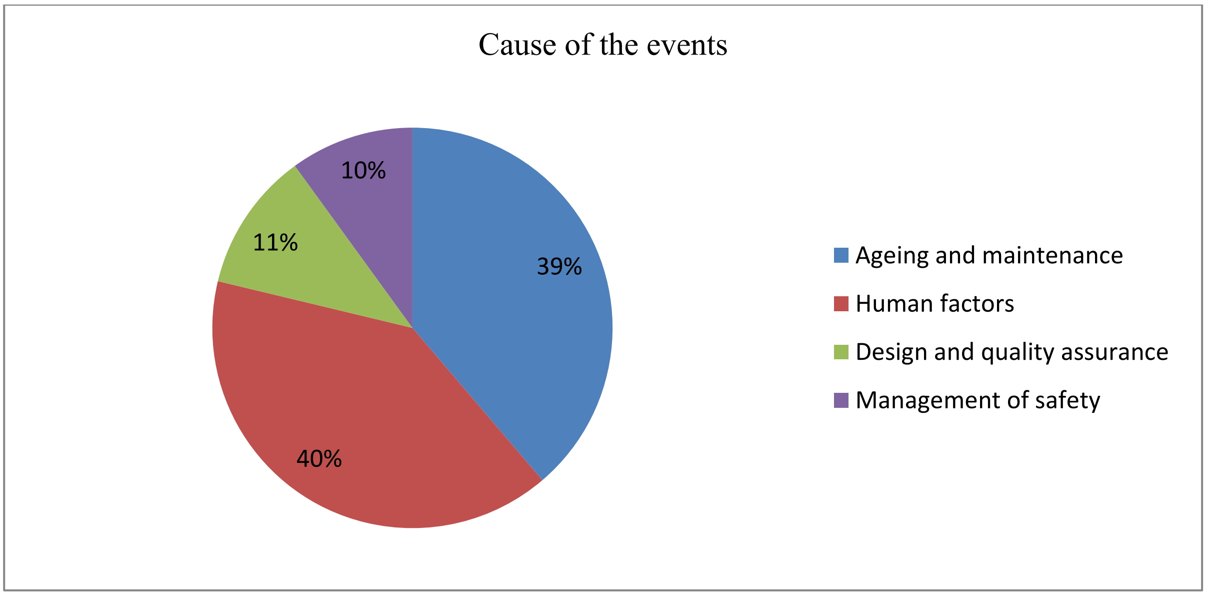

Fig.5. Distribution of the analysed events as per cause of events.

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 other 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, 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 deficiency 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 management oversight. In order to preserve the nature of the subject groupings, therefore, the analysis 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 the majority of the research reactors operating for more than 30 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 design, installation and commissioning deficiencies. These deficiencies are closely linked to shortfalls in the quality control system 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 reactors lifetime [8].

The following paragraphs describe deficiencies associated within 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 operational 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 established to be the root causes. Moreover, an inadequate use of operational 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 control, caused a control rod to become stuck in the fuel cell. The design deficiency was found to have existed since the system was commissioned.

An event report described that an unexpected ^{60}Co activity was detected in the primary cooling circuit. The inspection and analysis excluded a 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 under this category occurred in the 1950s and 1960s. In one event, pieces of the seal gasket (tetralin – an organic material) 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 also 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 primary coolant hold-up tank inner surface rubber liner got 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 got damaged. Another event occurred when a polyvinylchloride pipe was selected for the pool water demineraliser pipework; the damage to the pipework resulted in a partial drainage of the reactor pool.

4.1.1.3. Fuel

An event 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 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. Excessive vibrations of fuel assemblies were experienced 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.

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 in order 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 pipe line broke resulting in air ingress. The vent pipe wall thickness 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.

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 could be contained and extinguished without undue release of radioactive material but the material inside the hot cell facility containing paper and textile were destroyed and contamination of the hot cell facility took place. The investigation revealed that the dryer was not designed for this application. The technical specifications of the equipment for maintenance and testing were absent, as well as the relevant procedures.

In one event, ^{137}Cs activity was detected in the spent fuel storage pool. Spent fuel was stored either in a secondary aluminium barrel or 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 (not leak-tight) of secondary containers led to the corrosion of the secondary containers and that of 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, the failure of a preamplifier in the automatic power regulation circuit caused the power to increase as the control system detected reactor power to be lower than set power and so withdrew 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 limited the excess reactivity insertion.

Another event was related to the neutron measurement channels, the flooding of dry channels containing the ionization chambers of reactor neutron flux measurement caused the reactor scram. Flooding of the channels took place earlier during pumping of water from spent fuel storage pool to reactor pool. No protective devices were provided on the channels containing ionization chambers to prevent their flooding. Besides this design deficiency, lack of an approved operating procedure for pumping water from 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 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.

4.1.2. Safety significance

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

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/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. Inadequate management system (design review and quality assurance) resulted in 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 control rods design could have resulted in a common cause failure affecting multiple control rods. Such a situation could have caused more severe consequences.

Events such as flooding of ionization chambers or failure of the signal processing components that result in lower than actual signals detected by reactor control system can have potentially severe consequences as 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 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 to the environment.

4.1.3. Lessons learned

The following lessons are learned from the events reported under 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 reactor control system;
- Core thermal-hydraulic design 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 water.

4.2. EXPERIENCE WITH QUALITY ASSURANCE PROGRAMME

4.2.1. Summary of the root causes

The weaknesses of quality assurance programme, 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 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 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 past their irradiation period. Some event investigations identified that a possible cause was a deficiency in implementation of quality control during the container cold welding process. 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 fission-molybdenum. The failure occurred during irradiation in the reactor and poor welding and insufficient quality control of the capsule cover was identified to be the root cause. The event caused release of fission products in the cooling water system of the reactor. The event occurred in a reactor where several irradiations of similar targets have been performed.

Another more recent event identified that inadequate change control process led to a failure of 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 a lack of a monitoring programme caused galvanic corrosion that severely damaged the components. The subsequent investigation showed the redundant system also suffered the same problem.

During 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 cause of the event was 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 shortened from one year to six months. The event also brought out inadequacies in the field calibration and testing instrumentation to test full functionality of the sensors.

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 affects facility radiation levels and associated occupational doses. It also increases 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.

4.2.3. Lessons learned

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

- Inadequate quality control of fresh fuel was the most common cause of events with cladding failure. Using approved quality control procedures during the manufacture and post-manufacture fuel inspections are able to effectively minimise 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].

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 40% of the events reported can be directly attributed to human factors and another 10% 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 due to the procedure violations (non-compliance), inadequacies of the procedures, or errors of commission or omission on the part of concerned 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 bulged fuel rod, it could not be pulled inside 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 wide spread contamination of the reactor building. The highest exposure to an individual was 190 mSv and a massive clean-up 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 start-up source is inserted in the core of a reactor before start-up and removed after reaching a few watts of power level as per the operating procedure. In this event, the operator forgot to remove the Pu-Be start-up 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 had to be made for clean-up 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. Re-installation 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 as the reactor power was raised based on a faulty channel reading and other channels readings were not taken into account. Radioactivity release 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 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 and was required to be put in a shielded container in the reactor pool. As the crane was not functioning, the operators decided to remove the sample out of water without any shielding and put in the shielded container outside the pool. The container was not designed to shield the activity of the sample. The event resulted in high radiation fields while removing the sample and also around the shielded container due to in-sufficient shielding. The 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 operational limits and conditions included 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 start-up requirement in a pool type reactor wherein a basket used for preventing bypass flow around the fuel elements was not installed before reactor start-up. 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 an event, following some maintenance work, the solenoid valve on the piping connecting the storage water tank and 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 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.

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 what parts of the reactor protective system were to be inhibited and what parts were to remain operational, nor did it allow for the verification of which features 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 in fully, 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 reactor actual power being 2.3 times the indicated reactor power. The error was detected and corrected during the 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 primary cooling system components.

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 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 build-up in the container, the lid blew off liberating the trapped gases, which caused bubbles and the reactor scrammed on 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, no overexposure of personnel took place. The deficiencies in clearly communicating that the transfer flask has 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 by 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 not very high, he received 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.

4.3.1.3. Errors of commission or omission

In a high power heavy water moderated research reactor, with 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 sub-criticality 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 did not succeed 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 activity was released into reactor building. Substantial doses were consumed in the clean-up and restoration work.

In a critical assembly, the operator, in an attempt to save time, decided to reconfigure the core without an approved procedure 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-second with a peak power of 200 MW. The operator received a dose of 21 Gy gamma and 22 Gy neutron and died within 48 hours. Other people received 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 reaches 6 seconds. Due to an operator error, the wrong button was pressed causing a power excursion. Forty percent of the fuel elements were melted in the core.

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

In one event, in a critical facility, the supervisor instructed an operator to manipulate the control rods manually 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 power excursion was stopped by dropping second control rod and emptying vessel. The operator received a high dose of 5 Sv.

In one event, an experimental assembly was taken out of the reactor and during this operation, a part of the experimental assembly was left in the reactor and not investigated, this partially blocked the coolant flow in one position; later a fuel element was loaded in that position and due to less coolant flow, the fuel temperature reached the safety limit and failed. The event caused release of radioactivity into the coolant system and the environment.

In one event of the violation of operational limits and conditions, the operator set the overpower scram at 15% higher than 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 scram. Subsequently, proper tools were designed and the procedures were issued for such operations.

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 above 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.

Overall, the reported events are safety significant because the events have been 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, spread of radioactive contamination, inadvertent criticality, fire, and violation of operational limits and conditions. In some cases, the events were terminated safely as 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 also to be 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 be always 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, must 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 work place that can provoke error are noticeable, if people look for them. Error precursors are, by definition, prerequisite conditions for error and, therefore, exist before the error occurs. Many conditions can provoke error. The following error precursors are identified to have contributed to the events in the IRSRR:

- Time pressure;
- High workload;
- Lack of knowledge;
- Distractions/interruptions;
- Stress;
- Irreversible actions;
- Inaccurate risk perception;
- Over confidence/complacency;
- Impulsive response/action.

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

Events related to human factors and safety management demonstrate that management oversight and the timely communication of management expectations is 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/organizational factors on events investigations is getting higher attention.

A mature safety culture at the facility, shared equally and enthusiastically by all operating personnel, is indispensable to recognizing and preventing a potential event.

Many human performance tools such as self-checking, pre-evolution/job briefings, verification/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.

The significance of the human factors identified in the IRSRR review, demonstrates a weakness in the facility's safety culture. A strong safety culture requires that facility personnel do follow approved operating procedures; however, many of the reported events showed that personnel were willing to take short cuts, to achieve their goals.

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 especially for the lessons to be incorporated in facility processes and procedures [12].

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

- Established operating procedures and operational limits and conditions [13] were not followed by operating personnel or procedures were inadequate and did not specify actions required in the case of unexpected results during the performance of the procedure;
- Supervisors did not fulfil their expected oversight roles by becoming engaged in conducting activities;
- Operators did not fully understand or anticipate the effects of their actions [14];
- Risk was not recognized or inappropriately accepted by operators or the organization due to insufficient review and/or inadequate safety assessment;
- Organizational and leadership shortfalls allowed these weaknesses to go unrecognized and/or uncorrected.

4.4. EXPERIENCE WITH MAINTENANCE, INSPECTION AND PERIODIC TESTING

4.4.1. Summary of the root causes

Twenty one events reported to the IRSRR were assigned to maintenance, of which seventeen were related to mechanical maintenance, inspection and surveillance, and four to electrical, and instrumentation & control maintenance.

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 slip of a long-reach tool caused 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.

In the second event at a different facility, a known leak of the water of the secondary cooling system into the primary system was allowed to persist for more than six months, causing uncontrolled water chemistry of the primary system coolant. 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 due to the impossibility of determining with confidence the suitability for further irradiation of those assemblies that had not yet failed. Apart from the problem of high radiation inhibiting a close inspection, the fuel rods were also intensively coated with scale.

In an 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 twenty 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 ten and twelve 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 cause of the event was determined to be the slipped actuator cable from the cable reel causing the rod to over-travel and slippage of rheostat gear (position indicating device) from the axle of 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.

At another reactor, a primary cooling system pool inlet valve along with its actuator was removed for repair, and 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 recognise that the valve flanges had not been properly bolted and tightened the previous day, and proceeded to install the actuator and control devices and to re-commission 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 10000 gallons (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 three ton container to fall six metres to the floor. In the third case, the severely corroded crane rope broke while hoisting a twenty ton 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.

In another event, the quality of the primary coolant was seen to degenerate over time because the de-ionised water generator (supplying the facility make-up water) was being operated far beyond its manufacturers recommended period of use. This resulted from the fact that maintenance of the de-ionised 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.

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 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 also 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.

Other mechanical maintenance events at various facilities include: failure of a motor-pump coupling, leading to reduced primary flow; water leakage from a control rod seal due to inadequate preventive maintenance; over-irradiation and breakage of irradiation containers on failure of the transfer system due to lack of maintenance, or maintenance at too low a frequency; and leakage of pool water at two separate facilities due to poor maintenance on demineraliser 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 demineraliser 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 three hundred and fifty 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 again 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 event.

4.4.1.2. Electrical maintenance

Two events reported to the IRSRR are related to deficiencies in electrical maintenance activities: failure of a control rod to insert (scram) due to a short circuit in the electromagnet wiring which inadvertently maintained current to the magnet coil after the scram relay had opened; and failure of a secondary pump to stop on demand due to the arcing-closed of the power supply contactor relay. These two events are similar and are mainly due to inadequate or ineffective maintenance.

4.4.1.3. Instrumentation and control maintenance

At a research reactor facility a repeated failure of a newly installed digital instrumentation system to correctly present the positions of two control rods challenged the instrument technicians in many ways. The approach described in the event report seems to have followed a trial-and-error path over a period of two years before the problem seemed to have been solved, or at least 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 a second event, a neutron detector coaxial signal cable was found to have deteriorated, due to radiation exposure, to the point that the instrument was giving a completely inaccurate indication of the neutron flux during operation. The maintenance plan did not have any schedule for replacing the cable. The maintenance schedule was adjusted accordingly, in the light of this new information.

4.4.2. Safety significance

Fuel failures, real 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 maintenance inaction.

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 weld defects found 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 as the events indicate that some leaks can remain undetected for long time.

4.4.3. Lessons learned

The lessons learned from the events reported under 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 [15];
- 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;
- Post maintenance checks are as important as the maintenance work itself.

4.5. EXPERIENCE WITH AGEING OF SSCs

4.5.1. Summary of the root causes

Ageing is a general process in which characteristics of SSCs gradually change with time or use [16]. This process eventually can lead to failure of SSCs in performing their intended function. In broader term, maintenance is an ageing management process. However, many ageing issues develop or exist at research reactor facilities that cannot be addressed in the maintenance programme and require some 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 chapter. These events ranged from as early as 1980 right up to some of the most recent events.

Two events reported 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). These events were easily remedied by the replacement of the failed components, which suggests that the real issue is not adhering to the design service lifetime of such equipment. In particular, it was noted that the failed primary pump motor had seen 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 reported failure of SSCs due to fatigue: 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 secondary coolant pump shaft. 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 over-tightening of, the failed screw). The report regarding the sheared secondary pump shaft 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/motor assembly, or poor material quality of the shaft, bearing or impellor seizure.

The majority of the events under 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 as, while the decay tank is almost inaccessible for maintenance and inspection, the concrete enclosure allowed the ingress of rain water. In addition, the vent pipe connection to the aluminium decay tank was of galvanised 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 a research reactor facility, a buried waste water line provided for the transfer of both contaminated water to storage and uncontaminated waste water 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 the ground and ground water in the area. Levels of radiation 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 build-up 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 ground water. A maximum of 170 kBq/l was measured in the ground water. The reactor was shut down for two years to replace the ceramic tile liner with a metal liner (type of metal not specified), in order 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. The vessel wall had consequently 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/assessment of the SSCs.

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

An ineffective ageing management programme has led to contamination of the ground and ground water 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 under 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 contribute to preventing events and the resulting consequences;
- Maintenance programme has to consider ageing degradation of SSCs ;
- Increased attention has to be given to inspection and testing of SSCs important to safety;
- 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. The 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 be easily inspected have to be scrutinised 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 under development and the safety standards had not matured.

In case of sufficient negative temperature reactivity co-efficient 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.

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

In one case during 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 react on 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 on giving a trip command, three of the four control rods of 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 done by 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 to 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 forty fuel assemblies and five 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 that required lifting of the control rod by about 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 hit by the blast and two operators present just above the reactor were killed immediately. The third died shortly after his evacuation from the reactor building. The accident caused significant contamination to the environment. The root cause analysis showed several design deficiencies that include the requirement to lift control rod for assembly and disassembly, reactor becoming critical with the removal of the single central control rod, no mechanical limit while withdrawing control rod manually, use of burnable poison in control rods that caused rapid reactivity gain and reduction in shutdown margin over core life time.

In a heavy water moderated natural uranium fuelled critical assembly, the reactor power is controlled by heavy water level and cadmium rods are 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 (BF3 chambers), two were showing similar values and third detector showed erratic reading. Not realizing the impact of their action, the operators disconnected the third detector and continued the reactor operation. One of the experimenter smelled ozone and the reactor was shut down after few minutes.

Later investigations showed that two chambers believed to be reading correctly had actually saturated and reactor operated at unknown power. The six persons present received high doses (2.05 Sv to 4.33 Sv), one died and 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 reactor, criticality is achieved by a combination of fuel elements insertion and control rods withdrawal. During the loading of the reactor with fuel elements, a power excursion occurred. After the loading of five fuel elements, the control rods were withdrawn to check the criticality. 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 was seen and the reactor tripped on overpower. The protection against too short a 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.

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 to environment and contamination spread within and out of reactor facility. Among the events reported to IRSRR, these are the ones where loss of life/limbs has been reported. These are also the events where reactors have been destroyed beyond recovery.

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, start-up, 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 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 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) have to be performed according to approved operating procedures [17]. 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 dropping the moderator or a second system of absorbing material. This has to be considered during the design of an experimental device also, 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.

4.7. EXPERIENCE WITH UTILIZATION AND MODIFICATIONS

4.7.1. Summary of the root causes

Utilization of a research reactor changes in many cases during its lifetime. New experiments are introduced and irradiation programmes are changing as a consequence of different demands. These changes can introduce new risks which must be evaluated. A number of events were reported to the IRSRR on damage of materials during irradiations described below:

4.7.1.1. Failure of the irradiation capsule

An incident of a TeO_2 capsule burning in a thimble tube is reported, in which 3.7^x10^{11} Bq of ^{131}I was released in the pool and an estimated 1.85^x10^7 Bq of ^{131}I to 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 products 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^x10^{13} Bq of noble gases and 3^x10^{13} Bq of iodine was released into coolant system; and, 1.85^x10^{13} Bq of noble gases and 1.85^x10^7 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 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 ten 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 coolant system and ventilation system. The subsequent investigations revealed that 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.

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 higher-than-allowed power level. In a fast reactor, an irradiation device was found to be mechanically damaged by the 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 scram due to high radiation levels on pool top. The corrective actions included 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 molybdenum production. The break was caused by severe vibrations in the target holders. The inner structure was redesigned in order to avoid these vibrations and a periodic inspection program 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.

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 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 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 and the same was lowered below the pool water level to bring down the radiation level.

In another event, an irradiation capsule filled with xenon got 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 no damage was done, but it just as easily could have been irradiated at higher power level with undesirable consequences.

4.7.2. Safety significance

The consequences of the events described above were usually limited due to the small quantities of material involved. It is to be noted that activated aluminium capsule can be a greater source of radiation field than the sample material itself, especially immediately after removing it from the reactor core. In a number of cases the events led to unnecessary doses (even though not excessive) to the operating personnel or to contamination of personnel and work-areas. However, the consequences of such events could be more severe if chemically reactive or poisonous materials are irradiated.

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. Following lessons can be learned from the events reported to the IRSRR under this category:

- In case of introducing new irradiation programmes, a safety assessment in accordance with the safety significance of the programme is essential [18];
- 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 must be regularly inspected and maintained, with the same attention as the reactor components themselves;
- Handling of irradiation samples have 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.

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 over-exposure 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 dose mainly due to non-adherence to the established procedures.

In one event, the personal dosimeter of a maintenance officer recorded a high value of 35 mSv over 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 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 place, periodic checks for detecting unknown radioactive materials in high occupancy zones and reinforcement of radiation detection of materials at the exit of 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.

An event reported high radiation dose on the fingers of an operator, who 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 use of tools.

In one event, personnel present in the reactor hall got 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 in the pool water. The alarm set points of radiation monitors were not reached although the radiation monitors showed an increasing trend.

4.8.2. Safety significance

All the events discussed above caused radiation exposure to personnel, which was avoidable. Although none of the events resulted in an exposure above the dose limits, some of the events had the potential for it.

4.8.3. Lessons learned

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

- Ensure that all staff adhere to radiation protection procedures [19];
- 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 like earthquakes, storms, tsunamis, floods, lightning, extensive fouling of water intakes, 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 design basis of the facility. The serious consequences of the Fukushima-Daiichi nuclear power plant accident showed the importance of careful consideration and assessment of the external hazards [20, 21].

A single earthquake event is 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.

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.

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 but had no important safety consequences for the reactor and environment.

Despite a limited operational experience of research reactors with external hazards, the following lessons can be learned to improve safety:

- The robustness of the reactor SSCs to withstand external events and to assure basic safety functions has to be reassessed as per 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.

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. CONCLUSION

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 fifty-six participating Member States. The analysis of these events also clearly illustrates that many events could have been avoided if the operating experience from similar events was properly used. In some cases, similar events have recurred in the same facility indicating ineffective mechanism for operating experience feedback. Sharing the operating experience nationally and internationally will help operating organizations in taking preventive measures to reduce the frequencies and consequences of the events. The IRSRR is an important tool for sharing operating experience; however its effectiveness depends on the participation of its members through the timely submission of events in their research reactors.

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

Design and quality control

The events where design and quality control deficiencies were identified as the root cause highlighted the need for adequate design reviews and appropriate quality control, including modifications and experimental devices. Some of the design deficiencies remain latent and may go unnoticed for long periods of time, and then finally revealed through an event. Several events related to fuel performance were attributed to the design deficiencies and inadequate quality control. 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 not adequate care was taken while selecting the material for the service conditions of the components, resulting in their failures and in some cases significant consequences. Deficiencies in the layout of the primary cooling system components were identified as one of the causes for some of these events.

A significant number of the events indicated that design deficiencies have 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/or modification of SSCs need to be emphasized to ensure safety. 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 non-effective 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 effective control of the reactor, trained and qualified operating personnel, and strong safety culture could achieve this goal. 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, subtle declines in standards and performance that went unnoticed and evolved into a significant drop in standards, lack of supervision, shortfalls in competencies, tolerance of equipment or personnel problems, insufficient engagement of all those involved in decision-making, and ineffective use of operating experience to prevent the events. A questioning attitude has to be encouraged at all levels of staff at the facility, social hierarchy and cultural dogma sometimes makes this difficult to achieve. Many of the events reported to the IRSRR may have been avoided if the operating personnel had questioned the prevailing practices.

Most of the events under this category show that if the personnel involved had followed the procedures, and if the availability of these procedures and their implementation were ensured, the number of events would have been significantly lower. 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 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 problem.

An adequate management system is an effective measure in event prevention. In addition to other elements, this has to promote strong safety culture and foster a questioning and learning attitude by the operating personnel.

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 degradation cannot be addressed in a routine maintenance programme and require special attention in the form of a refurbishment project. Undetected corrosion of pipes 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 and radiation damage of the components are other important contributors to the events related to ageing in research reactors. The events under this category also show that most of the components affected have been the mechanical components with few events concerning electrical, and instrumentation and control system. These events highlighted the need for establishing in a timely manner, an effective ageing management programme that integrates maintenance, periodic testing and inspection programme. The ageing management programme has to identify all relevant ageing mechanisms and provisions to detect, monitor and trend ageing degradation of SSCs in order to implement suitable minimization and mitigation measures.

Experimental devices, which are specific to research reactors, have been associated with a number of events caused by ageing degradation and 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 some events 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 of the reactor areas. These are the only events reported to the IRSRR where deaths of operating personnel have occurred. Events related to inadvertent reactivity additions reported to 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. 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.

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. 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.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guide on Incident Reporting System for Research Reactors, IAEA, Vienna (2011).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Improving the International System for Operating Experience Feedback, INSAG-23, IAEA, Vienna (2008).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, A System for the Feedback of Experience from Events in Nuclear Installations, IAEA Safety Standards Series No. NS-G-2.11, IAEA, Vienna (2006).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Research Reactors, IAEA Safety Standards Series No. NS-R-4, IAEA, Vienna (2005).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Code of Conduct on the Safety of Research Reactors, IAEA, Vienna (2005).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSR Part 4, IAEA, Vienna (2009).

[7] ZIEDELIS S., NOEL M., Comparative Analysis of Nuclear Event Investigation Methods, Tools and Techniques, Joint Research Centre Scientific and Technical Reports, Institute for Energy, European Commission, (2011).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).

[9] 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, IAEA, Vienna (2012).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Research Reactors and Preparation of the Safety Analysis Report, IAEA Safety Standards Series No. SSG-20, IAEA, Vienna (2012).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Strengthening the Global Nuclear Safety Regime, INSAG-21, IAEA, Vienna (2006).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Operational Limits and Conditions and Operating Procedures for Research Reactors, IAEA Safety Standards Series No. NS-G-4.4, IAEA, Vienna (2008).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, The Operating Organization and the Recruitment, Training and Qualification of Personnel for Research Reactors, IAEA Safety Standards Series No. NS-G-4.5 IAEA, Vienna (2008).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Maintenance, Periodic Testing and Inspection of Research Reactors, IAEA Safety Standards Series No. NS-G-4.2 IAEA, Vienna (2006).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10, IAEA, Vienna (2010).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Core Management and Fuel Handling for Research Reactors, IAEA Safety Standards Series No. NS-G-4.3, IAEA, Vienna (2008).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety in the Utilization and Modification of Research Reactors, IAEA Safety Standards Series No. SSG-24, IAEA, Vienna (2012).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Radioactive Waste Management in the Design and Operation of Research Reactors, IAEA Safety Standards Series No. NS-G-4.6, IAEA, Vienna (2008).
[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Reassessment for Research Reactors in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, Safety Report Series No. 80, IAEA, Vienna (2014).
[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience 2009-2011, IAEA, Vienna (2012).

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 sixty criticality accidents that occurred since the early years of nuclear technology. Out of these, thirty-three accidents occurred at critical facilities, and five in other research reactors. All these reactor accidents happened during shutdown, start-up or low power operation. Some of these events are also mentioned in the IRSRR database. The thirty-eight accidents in research reactors resulted in twelve fatalities. In ten cases the installation was severely damaged. This overview indicates that criticality accidents are the worst possible accidents with research reactors. Compared to nuclear power plants, 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, 2ND 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 with 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 with 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 to 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 is of particular interest to research reactor community, which is not reported to the IRSRR.

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 done 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 completely destroyed. Contamination remained limited due to the low burn up of the fuel (0.1%).

The EBR-I accident demonstrated that experiments must be carefully prepared. Safety systems must 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 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. However, other sources are available which also contain useful information. The overview report from the IAEA and Nuclear Energy Agency's international reporting system for operating experience (IRS), which deals with nuclear power plant events contains a number of lessons learned. See also Ref. [21]. The research reactor community can benefit by learning from these lessons that are valid for research reactors.

The important lessons learned from events at NPP that are relevant to research reactors are discussed below:

- Understanding of the design basis and retaining accurate and complete documentation since the commissioning of the facility is important. This is particularly important since most of 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 which 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 must stop and 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 nuclear 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 off-shore 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 IAEA safety standards and with 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 Fukushima Daiichi accident justify a revision of the safety analysis for these facilities through the performance of a safety reassessment.

IAEA has published a safety report series No. 80 on ‘safety reassessment of research reactors in the light of the accident at the Fukushima Daiichi nuclear power plant’. See also Ref. [20]. 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 provided 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 this report includes a review of the design basis accidents and design extension conditions of the 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.

ANNEX III

OPERATING EXPERIENCE PROGRAMME DESCRIPTION

III-1. GENERAL

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

IAEA Safety Standards NS-R-4 on 'safety of research reactors' establishes requirements on the use of operating experience in para 2.23 as "The operating organization shall establish a programme for the collection and analysis of operating experience. Safety significant information shall be disseminated to all those concerned"; in para 7.10. (o) as "Operational 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"; and in para 7.108 as "In conducting the safety assessments, the operating organization shall give due consideration to information drawn from operating experience and other relevant sources". IAEA Safety Standards NS-G-2.11 'A system for the feedback of experience from events in nuclear installations' provides the detailed guidance in this regard.

The primary objectives of a system for the feedback of operational 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 management to align the organization to effectively implement the operating experience programme. These policies include established thresholds and set criteria for expectations and priorities;
- Event identification and reporting is strongly encouraged at all levels in the organization;
- Timely identification and reporting of events is 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 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 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/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 focussed 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 operational 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 Ref. [9].

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 operational 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 operational 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 operational 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 operational experience feedback into its quality assurance/management system in accordance with national and international standards.

The event reporting has to be established in accordance with the licensing conditions and operational limits and conditions of the facility. The event reporting system includes the reporting criteria, format of the report, timeline for reporting and the individuals/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 (drawings, sketches, photos, process and instrumentation diagrams etc.) 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, start-up, 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/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 the 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/department responsible for authorizing or implementing corrective action may be identified.

The report has to clearly identify lessons learned. 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 operational experience is one of the most valuable parts of the process of feedback of operational experience.

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

CONTRIBUTORS TO DRAFTING AND REVIEW

D'Arcy, A.	South African Nuclear Energy Corporation, South Africa
Hargitai, T.	International Atomic Energy Agency
Joppen, F.	Federal Agency for Nuclear Control, Belgium
Laslo, J.	Hungarian Atomic Energy Authority, Hungary
Lolich, J.	International Atomic Energy Agency
Mottl, V.	Australian Radiation Protection and Nuclear Safety Agency, Australia
Rao, D.	International Atomic Energy Agency
Shokr, A. M.	International Atomic Energy Agency
Waddel, T.	Consultant, United States of America

IAEA
International Atomic Energy Agency

No. 23

ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

AUSTRALIA
DA Information Services
648 Whitehorse Road, Mitcham, VIC 3132, AUSTRALIA
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: books@dadirect.com.au • Web site: http://www.dadirect.com.au

BELGIUM
Jean de Lannoy
Avenue du Roi 202, 1190 Brussels, BELGIUM
Telephone: +32 2 5384 308 • Fax: +32 2 5380 841
Email: jean.de.lannoy@euronet.be • Web site: http://www.jean-de-lannoy.be

CANADA
Renouf Publishing Co. Ltd.
5369 Canotek Road, Ottawa, ON K1J 9J3, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: http://www.renoufbooks.com

Bernan Associates
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

CZECH REPUBLIC
Suweco CZ, spol. S.r.o.
Klecakova 347, 180 21 Prague 9, CZECH REPUBLIC
Telephone: +420 242 459 202 • Fax: +420 242 459 203
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

FINLAND
Akateeminen Kirjakauppa
PO Box 128 (Keskuskatu 1), 00101 Helsinki, FINLAND
Telephone: +358 9 121 41 • Fax: +358 9 121 4450
Email: akatilaus@akateeminen.com • Web site: http://www.akateeminen.com

FRANCE
Form-Edit
5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: fabien.boucard@formedit.fr • Web site: http://www.formedit.fr

Lavoisier SAS
14 rue de Provigny, 94236 Cachan CEDEX, FRANCE
Telephone: +33 1 47 40 67 00 • Fax: +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

L'Appel du livre
99 rue de Charonne, 75011 Paris, FRANCE
Telephone: +33 1 43 07 50 80 • Fax: +33 1 43 07 50 80
Email: livres@appeldulivre.fr • Web site: http://www.appeldulivre.fr

GERMANY
Goethe Buchhandlung Teubig GmbH
Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 8740 • Fax: +49 (0) 211 49 87428
Email: s.dehaan@schweitzer-online.de • Web site: http://www.goethebuch.de

HUNGARY
Librotade Ltd., Book Import
PF 126, 1656 Budapest, HUNGARY
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472
Email: books@librotade.hu • Web site: http://www.librotade.hu

INDIA
Allied Publishers
1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 2261 7926/27 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell
3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: http://www.bookwellindia.com

ITALY
Libreria Scientifica "AEIOU"
Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: http://www.libreriaaeiou.eu

JAPAN
Maruzen Co., Ltd.
1-9-18 Kaigan, Minato-ku, Tokyo 105-0022, JAPAN
Telephone: +81 3 6367 6047 • Fax: +81 3 6367 6160
Email: journal@maruzen.co.jp • Web site: http://maruzen.co.jp

NETHERLANDS
Martinus Nijhoff International
Koraalrood 50, Postbus 1853, 2700 CZ Zoetermeer, NETHERLANDS
Telephone: +31 793 684 400 • Fax: +31 793 615 698
Email: info@nijhoff.nl • Web site: http://www.nijhoff.nl

Swets Information Services Ltd.
PO Box 26, 2300 AA Leiden
Dellaertweg 9b, 2316 WZ Leiden, NETHERLANDS
Telephone: +31 88 4679 387 • Fax: +31 88 4679 388
Email: tbeysens@nl.swets.com • Web site: http://www.swets.com

SLOVENIA
Cankarjeva Zalozba dd
Kopitarjeva 2, 1515 Ljubljana, SLOVENIA
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35
Email: import.books@cankarjeva-z.si • Web site: http://www.mladinska.com/cankarjeva_zalozba

SPAIN
Diaz de Santos, S.A.
Librerias Bookshop • Departamento de pedidos
Calle Albasanz 2, esquina Hermanos Garcia Noblejas 21, 28037 Madrid, SPAIN
Telephone: +34 917 43 48 90 • Fax: +34 917 43 4023
Email: compras@diazdesantos.es • Web site: http://www.diazdesantos.es

UNITED KINGDOM
The Stationery Office Ltd. (TSO)
PO Box 29, Norwich, Norfolk, NR3 1PD, UNITED KINGDOM
Telephone: +44 870 600 5552
Email (orders): books.orders@tso.co.uk • (enquiries): book.enquiries@tso.co.uk • Web site: http://www.tso.co.uk

UNITED STATES OF AMERICA
Bernan Associates
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Co. Ltd.
812 Proctor Avenue, Ogdensburg, NY 13669, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: http://www.renoufbooks.com

United Nations
300 East 42nd Street, IN-919J, New York, NY 1001, USA
Telephone: +1 212 963 8302 • Fax: 1 212 963 3489
Email: publications@un.org • Web site: http://www.unp.un.org

Orders for both priced and unpriced publications may be addressed directly to:

IAEA Publishing Section, Marketing and Sales Unit, International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22488 • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

15-03611

International Atomic Energy Agency
Vienna
ISBN 978–92–0–100615–8
ISSN 1011–4289