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Root cause analysis for fire events at nuclear power plants

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FOREWORD

Fire hazard has been identified as a major contributor to a plant's operational safety risk; the international nuclear power community (regulators, operators, designers) has been studying and developing tools for defending against this hazard. Considerable advances have been achieved in the past two decades in design and regulatory requirements for fire safety, fire protection technology and related analytical techniques. Likewise, substantial efforts have been undertaken worldwide to implement these advances in the interest of improving fire safety both at new nuclear power plants and at those in operation.

The IAEA endeavours to provide assistance to Member States in improving fire safety in nuclear power plants. In order to achieve this general objective, the IAEA in 1993 launched a task on fire safety. The purpose of this task was to develop guidelines and good practices, to promote advanced fire safety assessment techniques, to exchange state of the art information between practitioners, and to provide engineering safety advisory services and training in the implementation of internationally accepted practices.

This TECDOC addresses a systematic assessment of fire events using the root cause analysis (RCA) methodology. This methodology is recognized as an important element of fire safety assessment. Experience shows that even incidents involving minor fire events, when analysed with this method, invariably yield a number of insights into causal factors which other methodologies might miss. If adequate and proper attention is given to these insights, most of which relate to procedures and policies, then the incidence of fire events can be significantly reduced.

The IAEA officer responsible for this publication was H. Tezuka of the Division of Nuclear Installation Safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

During the period 1993–1994, the IAEA task concentrated on fire safety and fire protection of operating plants with the main focus on the development of guidelines and good practice documents. The first task was the development of a Safety Guide [1] which formulated specific requirements for the fire safety of operating nuclear power plants. Several good practice documents [2–4] providing advice on fire safety inspection were developed to assist in the implementation of this Safety Guide. These documents were published in the IAEA NUSS Series as Safety Practices. These publications address all technical aspects of fire safety inspection at nuclear power plants (NPPs) including fire protection measures and fire fighting capability [2], fire protection system organization, management and procedural control [3], and evaluation of fire hazard analysis [4].

In the period 1995–1996 the task concentrated on the development of good practices in the preparation of fire safety analysis. Two documents providing advice on the preparation of systematic fire safety analysis at NPPs were published under the Safety Report Series: “Preparation of Fire Hazard Analyses for Nuclear Power Plants” [5] and “Treatment of Internal Fires in Probabilistic Safety Assessment for Nuclear Power Plants” [6].

The IAEA task on fire safety for 1997–1998 includes tasks aimed at promoting a systematic assessment of fire safety related events and disseminating the essential insights from this assessment.

This TECDOC addresses a systematic assessment of fire events using the root cause analysis (RCA) methodology. This methodology is recognized as an important element of fire safety assessment.

1.2. OBJECTIVES

The objective of this report is to promulgate the use of the ASSET[1] root cause analysis (RCA) methodology for application to the analysis of fire events. This publication is intended for use in the investigation of fire events by qualified experts, supported by fire specialists, operations and maintenance personnel and safety assessors, as appropriate.

1.3. SCOPE

This report presents an ASSET root cause analysis which is tailored to the investigation of fire events and is intended to supplement the existing ASSET guidelines [7] which provide general guidance on root cause analysis. The methodology is described and illustrated by reference to a hypothetical example and is then applied to three fire events. These events are based on real operational experience and illustrate the practical application of the methodology.

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[1] ASSET: Assessment of Safety Significant Event Teams. Since 1986, in the framework of its operating experience feedback system, the IAEA has been co-ordinating the ASSET service as an international mechanism to draw specific and generic lessons for the enhancement of the level of operating safety in NPPs and to circulate them among interested parties.

1.4. STRUCTURE OF THE REPORT

Section 2 describes the methodology of RCA in general. Section 3 provides the concluding summary of this report.

There are four annexes to the report. Annexes I–III provide three examples of the ASSET root cause analysis methodology applied to different fire events which have occurred in NPPs of IAEA Member States. Occurrences from each of the fire events are selected for analysis and assessment on the basis of the nature of the failures which brought on the occurrences and the safety significance (real or potential) of these occurrences. Annex IV provides a blank event root cause analysis form for copy and use.

1.5. PERSONNEL ATTRIBUTES FOR FIRE RCA

Root cause analysis should be implemented by a team approach, involving person(s) qualified to lead the analysis of root causes as well as appropriate specialists in areas such as fire protection, plant operations and maintenance, training, quality management and auditing. This list is not intended to be exhaustive, as each event will have its own subtleties and features. To the extent possible, the team should be independent.

The degree of independence, team size and team composition is a matter for individual operators to decide and is likely to be influenced by the type and severity of the event being assessed.

2. METHODOLOGY

As fire can significantly affect nuclear safety, it is important wherever possible to identify the potential causes of fires to prevent the ignition of combustible materials and to make provisions to contain and minimize the effects of any fire which may occur. In common with protection against other hazards, a defence-in-depth approach should be provided.

The occurrence of a fire event means that at least one of the protective measures has failed. It is vitally necessary to determine which protective measures failed and why they failed, as well as why the failure was not detected before the fire event occurred. The following adaptation of the ASSET root cause analysis method (as spelled out in [7]) offers a means of answering these questions.

This methodology allows to effectively evaluate fire events. It is not the intent of this report to preclude the use of other RCA methods which pursue the same objectives.

2.1. OVERVIEW OF THE METHODOLOGY

The fundamental approach to the ASSET methodology is shown in the following diagram:

DISTURBANCES TO
(NUCLEAR INSTALLATIONS)

SAFETY PERFORMANCE	
(1) WHAT HAPPENED?	***EVENTS***

OCCUR AND RECUR
BECAUSE OF

SAFETY PROBLEMS	
(2) WHY DID IT HAPPEN?	***DIRECT CAUSES***

DUE TO

SAFETY CULTURE	
(3)WHY WAS IT NOT PREVENTED?	***ROOT CAUSES***

Root cause analysis provides a tool for gaining further detailed insights into the causes of the fire event with particular attention to the identification of plant design, operation, surveillance, maintenance, training, procedures and policies which must to be improved to prevent repetition.

The basis of the ASSET root cause analysis of an event is the philosophy according to which:

Events result from preceding occurrences due to latent weaknesses that were not prevented by quality control, nor by preventive maintenance and that were not discovered by the plant surveillance and/or not covered by a feedback programm.

An occurrence exists when any element of equipment, personnel or procedure **fails to perform as expected**.

The root cause analysis is applied to an event, defined as a reportable failure. In this context, the term ‘reportable’ may be used for events reported which are internal or external to the plant and its headquarters and for mandatory reporting of significant events to the supervisory authorities. Most events are preceded by one or more occurrences in each of which a single element (of equipment, personnel or procedure) failed to perform as expected. The objective of the root cause analysis is to establish exactly what happened and why, so as to contribute to the prevention of repetitious events.

The root cause analysis is a process of three phases, namely:

Investigation:	the determination of what exactly happened, the identification of all the occurrences making up the event and their temporal and logical relationships
Analysis:	the analysis of selected (or all of the) occurrences
Formulation of recommendations:	the identification of corrective actions on which to base recommendations.

2.2. INVESTIGATION

The purpose of the investigation phase is to obtain a clear, logical picture of what happened in the period leading up to the event as well as during the event.

The information required to build up this logical picture will be derived from a range of sources, some of which are listed below:

- Station operating log
- Plant control log
- Workshop logs and journals
- Fire team logs
- Fire team incident reports
- Event reports (may be several at different times of origin)
- Investigation reports (may be several, each concerning specific areas of plant or activity)
- Interviews with plant personnel involved, either directly by the analysts or from transcripts taken during other parts of the investigations/inquiries
- Plant inspections
- Plant safety analysis report and technical specifications
- Construction, installation, maintenance records, etc.

The prime source of information is the discussion between the team members and their plant counterparts. It is thus very important to establish the rules of engagement. The team members should stress the importance of establishing a blame-free culture in the context of promoting a good safety culture. It should be pointed out that there is no interest in blaming individuals or groups of individuals. There must be an open flow of information in order to establish exactly what happened.

The outputs of the investigation phase are:

- a title for the event,
- a descriptive narrative,
- a chronological list of occurrences,
- a logic tree of the occurrences which make up the event.

2.2.1. Title of event

The title should indicate the nuclear safety implications of the event as well as the apparent lack, failure or deficiency that was involved. The following two examples illustrate this requirement:

- Degradation of the safety function “supply of emergency electric power” due to failure of a diesel generator to start during a scheduled test because of fire damage to control cables.

- Potential degradation of the safety function “cooling of the core” due to flooding in the high pressure core cooling pump room because of a fire in the adjacent compartment.

A common failure among inexperienced analysts is to adopt short titles for these events such as:

- Diesel generator 2 control system damaged;

- High pressure cooling pump room flooded.

Such short titles obscure the safety implications of the event and can lead to a response such as “so what?”.

2.2.2. Narrative

The narrative is a structured record of the event as derived from the investigation. The reader should be able to understand how the event unfolded in time and in logic. Short sentences or statements increase clarity. It should be easy to identify the individual occurrences, to find out what element failed and the nature of the failure.

The discipline of writing the narrative serves as a quality check on the investigation. The investigation should ask if the narrative gives a complete picture; if it does not, the concern should be formulated as a query. For example:

When did the occurrence or activity occur?

How much time elapsed between occurrences A and B?

What actions or activities were taking place in that interval?

Why was the interval so short (or so long)?

Who were those involved and why did they so act?

It may be necessary to return to previous information sources, particularly to the personnel involved, and to seek answers and clarification until the investigator is satisfied that the true picture has emerged — persistence may be needed.

The narrative is complete when it does not leave questions unanswered and when it gives a complete picture of the event in terms of the time sequence of the occurrences and as to the equipment, procedures and personnel involved.

Root cause analysis can be applied to any event. In order to explain and demonstrate the method the following hypothetical example is used to illustrate the level of detail which may be sought. This example is further used and developed in this and later sub-sections.

The following is a typical descriptive narrative which might be obtained as a result of the investigation phase.

04:21	Work order issued to welder to repair cable tray support in No. 6 turbine steam end cable race.
04:30	Maintenance foreman instructed welder to carry out the repair. Instruction given to place fire blanket between weld site and cables. Foreman did not visit site of work.
04:50	Welder collected access permit from permit office. Control room staff confirmed isolation of fire detection and fire extinguishing equipment. Access keys given to welder.
05:35	Welder finished the repair, removed his equipment, including the fire blanket, returned the access key and cancelled the permit.
05:40	Control engineering decided not to reinstate fire protection equipment (as history showed it to be time consuming, giving spurious alarm signals) because the day engineering staff wanted to inspect the repair.
07:25	No. 6 cooling water (CW) pump tripped No. 6A extraction pump tripped No. 6A feed pump tripped.
07:30	Turbine operator reported to control room “smoke coming from cable race access hatch”.
07:31	Fire brigade called as per standing instructions. Station fire alarm sounded. Cable race fire protection de–isolation commenced.
07:38	Station fire team attempted to enter cable race (wearing breathing apparatus). Heat prevented first attempt, but fire fighter noticed that rubbish was burning on the floor as well as cable insulation being on fire.
07:39	Fire water pumps confirmed as running.
07:40	Reactor temperature instrumentation began to show unusual indications, I&C fitter called to investigate.
07:52	I&C fitter reported by telephone, marshalling and monitoring (M&M) cubicle 6A found to be full of smoke with carbon deposit on terminal blocks.
07:53	Shift Manager instructed rapid controlled shutdown of reactor and of turbine 6. Turbine 5 to be used as a heat sink.
07:54	Control room informed that station fire team and fire brigade team have entered cable race.
08:00	Fire reported as being extinguished.
10:00	Initial inspection (after reactor cool down) report to the effect that evidence of considerable rubbish accumulation, evidence of oil seeping down the surface of a redundant pipe and dripping on to floor where rubbish accumulated. Cable race fire barriers had withstood the fire but sealing material around cable passing through the roof to the M&M cubicles above had failed.

2.2.3. Identification of occurrences

ASSET uses the term “occurrence” to describe the situation in which an element of equipment, personnel or procedure failed to perform as expected. The standard for what is expected is derived from the relevant specifications, e.g., design specifications and acceptance criteria for equipment and systems, work specifications and procedures for operational and maintenance work, training specifications and acceptance criteria for personnel and scope, style and quality specifications for procedures. Two examples are used for illustration, drawn from the above narrative.

(a) Consider the case of the accumulation of rubbish in the cable race. If the plant procedures did not call for routine inspection of the cable race and the expectation is that they should, then there is an occurrence in that the procedures failed to have adequate scope. If inspections are called for and adequately defined, then there would be an occurrence in that some person failed to follow the procedures.

(b) Consider the seal at the point at which the cables passed through the roof of the cable race into the marshalling and monitoring cubicle above. If the seal had been applied as part of the fire barrier arrangements, its failure would represent an occurrence of equipment failing to perform as expected — “fire barrier seal failed to withstand fire”. If, however, the seal had been applied only as part of a scheme to prevent CO_2 fire suppressant gas leaking from the M&M cubicle into the cable race and was not expected to withstand high temperature, its failure in the fire would not be an occurrence — it behaved as expected. In this case, the failure lies in the design and review process, in failing to recognize and specify the appropriate safety duty.

2.2.4. Chronological sequence of occurrences

The following is an example of a chronological sequence of occurrences, based on the example narrative given above:

Occurrence 1:	Continuous before event	Failure of relevant operating staff to organize inspections of cable race.
Occurrence 2:	Continuous before event	Failure of contractors to remove rubbish.
Occurrence 3:	04:30	Failure of maintenance foreman to observe that the welder's sense of safety awareness had become eroded.
Occurrence 4:	04:50	Failure of welder to appreciate all the hazards relating to his task.
Occurrence 5:	05:35	Failure of welder to ensure all was safe and cold before leaving the site of the work.
Occurrence 6:	05:40	Failure of control engineer to make arrangements for manual supervision of the cable race following his decision to leave fixed equipment isolated.
Occurrence 7:	07:40	Failure of material of cable seal to M&M cubicle to withstand fire.

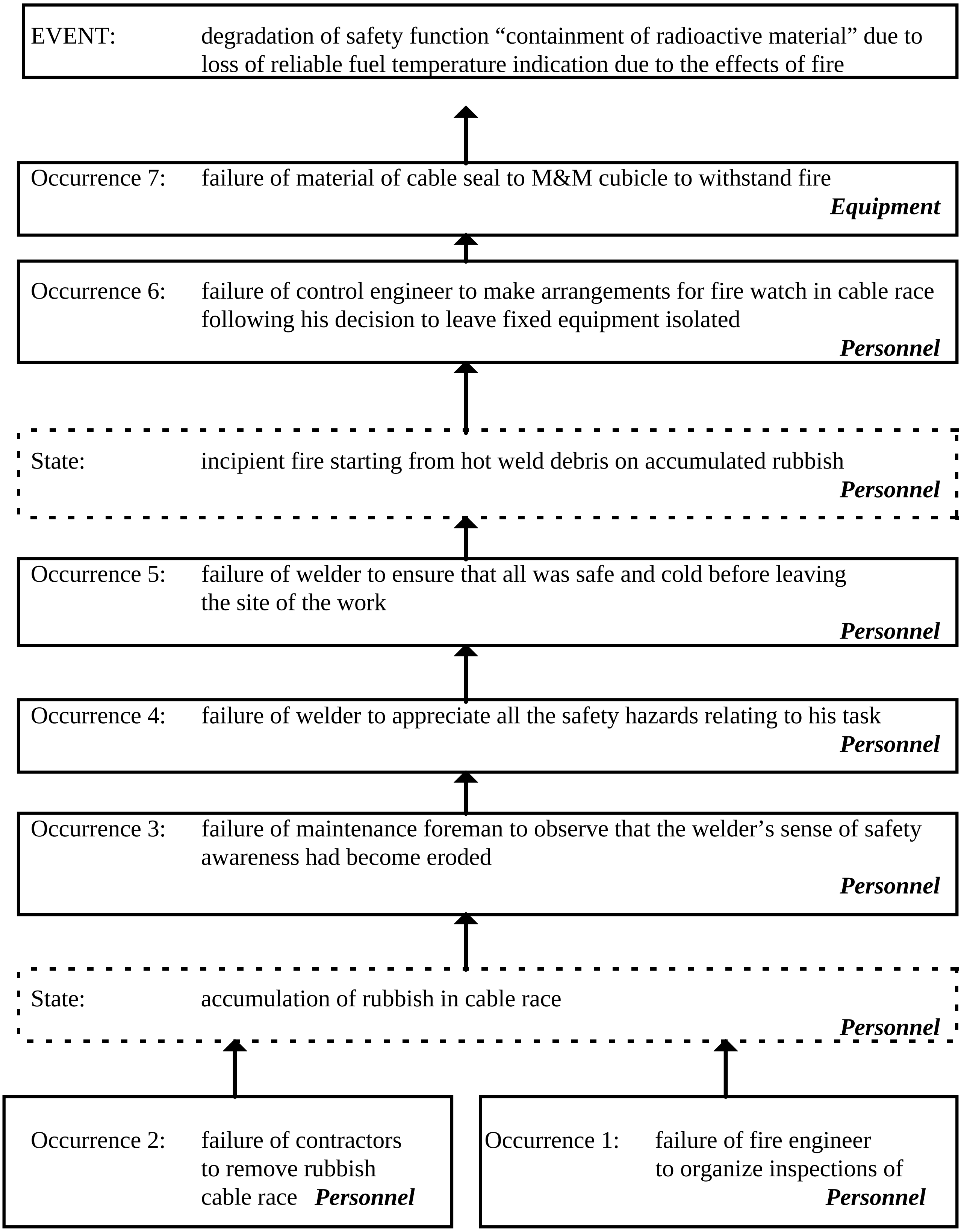

FIG. 1. Example of logic tree of occurrences.

Event: Potential for degradation of safety function “containment of radioactive material” due to loss of reliable fuel temperature indication due to the effects of fire.

It should be noted that occurrences (1) to (6) are failures of safety culture rather than equipment.

The reason for giving titles to the occurrences in the format of “something or someone fails to do a specified task, provide specific information, etc.”, is that it forces the analyst to identify and record what or who failed.

If occurrence (1) had been given the title: “Lack of inspections of cable race”, questions would remain as to whether a person had failed to organize the inspections when he was expected to do so, or that there was no requirement for inspections to be organized. It is necessary to differentiate between a personnel failure and a procedure failure.

It is important to identify quite closely which person or group of persons failed to perform as expected. This is because later in the analysis corrective actions in the shape of training and refresher courses will be discussed, and it will be necessary to know to which category the person(s) belonged who failed to perform as expected. Also, part of the corrective measures will be directed towards the individual(s) who failed, which makes it necessary to identify the person(s). Personal names, however, should not be included in a root cause analysis report.

The chronological order of occurrences is just another aid, like the title of an event and the narrative, to make sure that the right picture of the event has been established. If it is difficult to put the identified occurrences in the right order, there might still be some information missing in the narrative.

2.2.5. Logic tree of occurrences

The last step in answering the question “Exactly what happened?”, is to draw the logic tree of occurrences which is a schematic diagram illustrating the logical sequence in which the event unfolded and the logical relationships between the individual occurrences which make up the event.

An example of a logic tree of occurrences is shown in Fig. 1. In constructing the logic tree the following are noted:

- The earliest occurrence is shown at the bottom of the tree and the “event” is at the top.
- Two or more occurrences are shown in parallel if the succeeding occurrence depends on the existence of all of them, i.e. the event would not have progressed further if one of the parallel failures had not happened.
- Single occurrences, or groups of parallel occurrences, are shown in series if the upper is a logical consequence of the lower. To make it obvious why occurrences in series logically follow one another, it is sometimes helpful to indicate the situation or state which exists between them. The occurrences are shown in solid boxes, while the situation or state is indicated in a dotted box.

- Arrowed lines are used to indicate the logical connection between occurrences (and conditions).

- The occurrences in the logic tree are numbered for identification purposes.

- The nature of the occurrences is preferably indicated in the right hand margin of the page presenting the logic tree. This can be only one of three possibilities: equipment, procedure or personnel. The only purpose of identifying the nature of an occurrence is to make sure that the right picture of the event has been created. If the nature of the event is not quite clear, some information is still missing and must be obtained.

2.3. ANALYSIS

The root cause analysis is applied to some or all of the occurrences identified in previous phases. If only a selection of occurrences are to be analyzed then a brief note regarding the reasons for selection should be made. Occurrences chosen for analysis should be those judged to have the most significance for nuclear safety or those which offer the best insights into the safety culture at the plant.

The root cause analysis is in fact the process of completing the **event root cause analysis form** (ERCAF) shown in Annex IV. The essential elements are the identification of the **direct cause** and the **root cause**.

The **direct cause** is the latent weakness in the element which failed. The **root cause** is either the reason for which the latent weakness was not discovered before an in-service failure, i.e. a failure of the surveillance programme OR stems from the inadequate restoration of a previously recognized latent weakness.

The direct cause has contributors stemming from deficiencies in quality control and/or preventive maintenance programmes. The root cause has contributors which can only be deficiencies in the management of, or the policy for, surveillance and/or experience feedback.

The **title of the event**, the **number and the title of the occurrence** and the **nature of the occurrence** are as described in the previous sections and are entered into the appropriate boxes.

The latent weakness has to be determined by the analyst on the basis of the information in the narrative. From the example described above, the occurrence 4 is “failure of welder to appreciate all the hazards relating to his work”, the latent weakness might be expressed as “the welder's sense of prudent approach had degraded”. Similarly, occurrence 7 is “failure of material of cable seal to M&M cubicle to withstand fire” and the latent weakness might be expressed as “the material was inadequate for the required duty”.

The above examples show that a latent weakness typically is a weakness that does not immediately disturb the operational process but remains hidden until, under certain circumstances, it gives rise to a “failure to perform as expected”. The latent weaknesses are the direct cause. In occurrence 7, the latent weakness could have been prevented by quality control and/or preventive maintenance. The deficiencies in these programmes which allowed the failure to occur are known as contributors to the existence of the latent weakness and have to be identified and entered on the analysis form.

Quality control typically is performed prior to operation, which means quality control after manufacturing of components before they are stored for future use, examination of personnel after training before they are allowed to perform their job and validation of procedures before release for use at the plant. Effective quality control, preventive maintenance and surveillance require the availability of clear and comprehensive acceptance criteria as a reference basis.

Preventive maintenance is necessary to mitigate the degradation of the quality of equipment, procedures and personnel. Based on experience, on information from the manufacturers and taking into account the acceptance criteria, structured programmes can be designed for periodic overhaul, cleaning and exchange of components and equipment, periodic checks of procedures, refresher courses of personnel, etc.

Quality control and preventive maintenance programmes deal with expected degradation. Unexpected weaknesses and unexpected degradation are guarded against by the deployment of surveillance programmes. If an event has occurred, it means that the surveillance programme has been deficient. The analyst must identify the specific deficiency and enter it in the appropriate box on the form. Using the example given above, the surveillance deficiency in occurrence 1 might be “the engineering manager did not adequately monitor the approach of the fire engineer in the performance of his job”.

In filling in the root cause analysis form, the following should be taken into account:

Latent weakness of the element that failed to perform as expected	Each occurrence has by definition only one latent weakness. The corrective action should address this one latent weakness. The corrective action should include “who” is responsible to implement the corrective action.
Deficiency of quality control and/or preventive maintenance and/or acceptance criteria	This “contributor” to the existence of the latent weakness is a deficiency in the prevention of foreseen latent weaknesses. The corrective actions should address the deficiencies identified in quality control, preventive maintenance and acceptance criteria applied to the group of components, procedures or personnel which dealt with the element which failed. Again the corrective actions should include “who” is responsible for implementation.

Deficiency of surveillance programme and/or experience feedback	By ASSET definition, the root cause is a deficiency in the surveillance programme. Identify, in the “root cause” box of the root cause analysis form, the deficiency in the surveillance programme the which resulted in the latent weakness not being discovered. The corrective actions should address the identified deficiency in the surveillance programme and indicate the person responsible for implementation. Experience feedback is mentioned separately to stress the importance of including (external and internal) experience in the process of surveillance and corrective actions.
Deficiency of policy for, or management of, the surveillance programme and/or experience feedback.	The ASSET approach recognizes the importance of management policy and support for organizational measures like programmes for quality control, preventive maintenance and surveillance. Therefore, the ASSET root cause analysis specifically addresses these aspects of management.

It must be pointed out that the corrective actions to be entered in the right-hand boxes of the root cause analysis form should be both practically and economically feasible measures which support the organization, its staff and management in the enhancement of the prevention of incidents. Because different levels in the organization are addressed, it is important to include the appropriate levels of responsibility in defining these corrective actions.

As mentioned above, each occurrence relates to one latent weakness. However, the deficiencies in quality control, preventive maintenance, acceptance criteria and surveillance and their corrective actions usually have broader implications. In particular, policy and management aspects influence other areas in the prevention of incidents. This means that plant personnel, performing ASSET root cause analysis of many events, should produce corrective actions for each one of the identified latent weaknesses, but should combine the results of analysis of related events to create a comprehensive recommendation for corrective action in connection with quality control, preventive maintenance, acceptance criteria and surveillance. A similar course should be followed in formulating corrective actions regarding management and policy aspects.

Three root cause analysis forms, based on the narrative provided in Section 2.2.2, are shown in Figures 2–4.

<table>
<tr><th colspan="2">IAEA</th><th colspan="4">EVENT ROOT CAUSE ANALYSIS FORM</th><th colspan="6">ASSET</th></tr>
<tr><td colspan="2">Event title:</td><td colspan="4">Degradation of safety function containment of radioactive material due to loss of reliable fuel temperature indication due to the effects of fire.</td><td colspan="6">Safety consequences due to initiating failure</td></tr>
<tr><td colspan="6">SAFETY PERFORMANCE:
OCCURRENCE: What failed to perform as expected?</td><td colspan="6" rowspan="2">Corrective actions by plant</td></tr>
<tr><td colspan="2">Occurrence title:</td><td colspan="4">Occurrence 4. Failure of welder to appreciate all the hazards relating to his task.</td></tr>
<tr><td colspan="2" rowspan="3">Nature of the failure</td><td>X</td><td>Personnel failure</td><td>Occurrence results from a failure during operation</td><td></td><td colspan="2" rowspan="3">Ap-pro-pri-ate</td><td colspan="2" rowspan="3">Com-pre-hen-sive</td><td colspan="2" rowspan="3">Im-ple-ment-ed</td></tr>
<tr><td></td><td>Equipment failure</td><td rowspan="2">Occurrence results from a deficiency discovered by periodic testing</td><td rowspan="2"></td></tr>
<tr><td></td><td>Procedure failure</td></tr>
<tr><td colspan="4">SAFETY PROBLEMS:
DIRECT CAUSE: Why did it happen?</td><td colspan="2">How to eliminate the problem?
(Corrective actions by ASSET method)</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">Latent weakness of the element that failed to perform as expected</td><td colspan="2">Welder’s sense of prudent approach was degraded.</td><td colspan="2">I Foreman to discuss need for prudent approach and remind of his role in promoting and ensuring safety. Reinforce training of all work groups in area of safety culture.</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the latent weakness:</td><td colspan="2" rowspan="3">Training and assessment programme did not address levels of safety awareness.</td><td colspan="2" rowspan="3">II Training officer to review scope of end of training assessments.

Consider introduction of the STAR programme.</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Not qualified prior to operation. Poor quality control</td><td></td></tr>
<tr><td>Qualification degraded during operation. Poor preventive maintenance</td><td></td></tr>
<tr><td colspan="4">SAFETY CULTURE:
ROOT CAUSE: Why was it not prevented?</td><td colspan="2">How to prevent recurrence? (Corrective actions by ASSET method)</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td colspan="2">Deficiency in timely eliminating the latent weakness:</td><td colspan="2" rowspan="3">Foreman failed to observe that the welder’s prudent approach had become impaired.</td><td colspan="2" rowspan="3">III Maintenance manager to revise training of supervisors and review job descriptions to improve their surveillance of the performance and attitudes of their staff.</td></tr>
<tr><td>Detection</td><td></td></tr>
<tr><td>Restoration</td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the deficiency

Inadequate policy for:</td><td colspan="2" rowspan="3">Policy statements regarding the role of supervisors in ensuring that safety awareness is maintained at a high level were vague and unfocused.</td><td colspan="2" rowspan="3">IV Plant manager to review policies in the area of safety culture and devise programmes to promote and implement the revised policies.</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Surveillance</td><td></td></tr>
<tr><td>Feedback</td><td></td></tr>
</table>

FIG.2. Example of root cause analysis — occurrence 4.

IAEA		EVENT ROOT CAUSE ANALYSIS FORM		ASSET					
Event title:		Degradation of safety function containment of radioactive material due to loss of reliable fuel temperature indication.		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title:		Occurrence 6. Failure of control engineer to make arrangements for manual supervision of the cable race following his decision to leave the fixed equipment isolated.							
Nature of the failure	X	Personnel failure	Occurrence results from a failure during operation	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
		Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		The control engineer's sense of prudent approach had degraded.	**I** Operations manager to review with the shift team the need for a constant questioning attitude and awareness of safety issues, and to establish a sound safety culture at all staff levels.						
Contributor to the existence of the latent weakness:		Shift manager failed to review the attitudes and behaviour of his team members. There were no acceptance criteria for these attributes.	**II** Operation manager to arrange for training and guidance for his supervisors in the matter of monitoring the attitudes and approach of all staff in the field of safety.						
Not qualified prior to operation. Poor quality control									
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		The surveillance of the performance and attitudes of staff failed to detect the latent weakness in the control engineer.	**III** Human resources manager to review means of establishing effective surveillance of personnel's effectiveness and attitudes towards safety.						
Detection									
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		Inadequate application of plant policies aimed at fostering a prudent approach and safety awareness.	**IV** Plant manager and departmental heads to review policy and its application across all disciplines.						
Surveillance									
Feedback									

FIG. 3. Example of root cause analysis — occurrence 6.

IAEA		EVENT ROOT CAUSE ANALYSIS FORM		ASSET					
Event title:		Degradation of safety function containment of radioactive material due to loss of reliable fuel temperature indication.		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: OCCURRENCE: What failed to perform as expected?				Corrective actions by plant					
Occurrence title:		Occurrence 7. Failure of material of cable seal to M&M cubicle to withstand fire.							
Nature of the failure		Personnel failure	Occurrence results from a failure during operation	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
	X	Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: DIRECT CAUSE: Why did it happen?			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		Seal material was such as to breakdown mechanically when exposed to high thermal gradients.	**I** Engineering department to select a more suitable material and arrange qualification tests before applying to service.						
Contributor to the existence of the latent weakness:		No pre-service qualification tests had been carried out.	**II** Technical department to consult with fire protection specialists to determine appropriate tests and acceptance criteria for selection of new material.						
Not qualified prior to operation. Poor quality control									
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: ROOT CAUSE: Why was it not prevented?			**How to prevent recurrence? (Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		Fire protection surveillance programme failed to detect presence of unqualified seal material	**III** Engineering manager to review scope and content of surveillance programme.						
Detection									
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		Inadequate policy for the control of materials and equipment used in fire protection/confinement applications.	**IV** Engineering manager to review scope and content of surveillance programme.						
Surveillance									
Feedback									

FIG. 4. Example of root cause analysis — occurrence 7.

2.4. FORMULATION OF RECOMMENDATIONS

For each occurrence analysed, corrective actions are suggested to eliminate the latent weakness identified, bearing in mind that prevention of repeated failures is paramount. For example, if a failed piece of equipment has, for some compelling reason, to be replaced by an identical piece of equipment, the corrective action should also address the frequency of maintenance and/or surveillance testing to prevent further failures. Similarly, if the occurrence involves personnel and the corrective action proposed concerns training or refresher training, attention should also be given to the frequency of refresher training and to the end of training testing (pre-service qualification).

The recommended corrective actions relating to the contributor to the latent weakness should specifically address the quality issues identified in the analysis. The aim is that future quality control and maintenance activities will ensure that further failures are avoided.

The corrective actions offered to address the root cause identified in the analysis should be specific enough to ensure that the latent weakness will in future be identified before an in-service failure and/or restoration activities are of sufficient quality to avoid future in-series failures.

The contributors to the root cause lie in the formulation of policies and their execution. The outcome of event investigation should contain focused suggestions for improving policy and/or its implementation to ensure future effectiveness of surveillance.

3. SUMMARY

The ASSET root cause analysis methodology has been applied to three plant fire events and demonstrate the insights which can be obtained by use of this method. The following advantages of the method are highlighted:

- it is inferred that the analysis of past events is both feasible and practicable;
- the application of the ASSET approach can identify deficiencies and weaknesses in the field of quality control, surveillance and safety culture;
- the method encourages structured and targeted corrective actions to be produced; and
- the implementation of corrective actions will reduce the potential for similar fire events.

Annex I

REFERENCE PLANT 1

I.1. EVENT DESCRIPTION (NARRATIVE)

Reference plant 1 is a twin unit 220 MW(e) pressurized heavy water reactor (PHWR).

Initial status of the plant

Unit 1 was operating at a power level of 185 MW(e) and Unit 2 was in a shutdown state with primary heat transport (PHT) in cold and pressurised state.

Brief description of the event

At 03:31:40 (T = 0) on 3 March 1993 the turbine of Unit 1 tripped. Simultaneously, a strong and powerful sound resembling an explosion was heard by control room staff on duty inside and outside the turbine building. Vibrations on the floor were also experienced by the control room staff. On investigation, a huge fire was observed on the operating floor and below near the slip ring end of the generator. Fire near the turbogenerator (TG) set of Unit 1 with bluish flames was also observed by the crane operator from his crane cabin parked on the side of Unit 2.

The reactor was tripped manually and the crash cooldown of the PHT system started. The PHT pumps tripped. There was a complete loss of electric power supply and control power supply to the plant because of burning cables. All indications and alarms were lost in the control rooms. A large amount of smoke entered the control room, causing the control room staff to evacuate the control room. No indications and alarms were available for Unit 1 including those in the supplementary control room.

Ten minutes after the initial event, two diesel engine driven fire water pumps were started. After one hour, fire water was manually injected into the steam generators (SGs). The fire was extinguished in close to one hour and 30 minutes by the station fire fighting services with the help of fire tenders from the outside agencies. One emergency diesel generating set could be started after some six hours and loads sequentially connected. One shutdown cooling pump could be started after 17 hours and normal decay heat removal function was restored.

I.2. EVENT TITLE

Potential degradation of safety function “cooling of fuel” and “control of reactivity” due to loss of electrical power, control and instrumentation cables, and loss of control room habitability due to smoke ingress, as a result of a major fire in the turbine hall.

I.3. CHRONOLOGICAL LIST OF OCCURRENCES

Occurrence 1:	Failure to act in a timely manner in accordance with international experience in the field of the safety consequences of turbine blade failure
Occurrence 2:	Turbine blade failure

Occurrence 3: Failure to replace fire barrier after maintenance/modification

Occurrence 4: Failure of fire barriers to contain the spread of fire

Occurrence 5: Failure of ventilation to prevent smoke ingress into control room

Occurrence 6: Failure of cable segregation to prevent common mode failure

Occurrence 7: Loss of shutdown cooling pumps

Occurrence 8: Loss of auxiliary steam generator feedwater pumps

Occurrence 9: Loss of second shutdown system (automatic liquid poison addition system)

Occurrence 10: Loss of alarms and indications in the main and supplementary control rooms.

I.4. LOGIC TREE OF OCCURRENCES

The logic tree of occurrences for this event is shown in Figure I.1.

I.5. SELECTION OF OCCURRENCES TO BE ANALYSED

All occurrences are important. However, the following are selected for an assessment because of their direct influence on the development of the fire event:

Occurrence 3: Failure to replace fire barriers

Occurrence 4: Failure of fire barriers to contain the spread of fire

Occurrence 6: Failure of cable segregation to prevent common mode failure.

I.6. ROOT CAUSE ANALYSIS OF SELECTED OCCURRENCES

Figures I.2–I.4 show the completed root cause analysis forms for the three occurrences selected in I.5.

I.7. CORRECTIVE ACTIONS

Since the event occurred, various rehabilitation works have been carried out in Unit 1. These include:

- assessing of the extent of damage to the civil structure during the incident and restoring it to its original strength;
- replacing the turbine generator;
- cable re-routing;
- replacing the PVC cables by FRLS (fire retardant low smoke) cables; and,
- providing fire barriers and fire stops at the required locations.

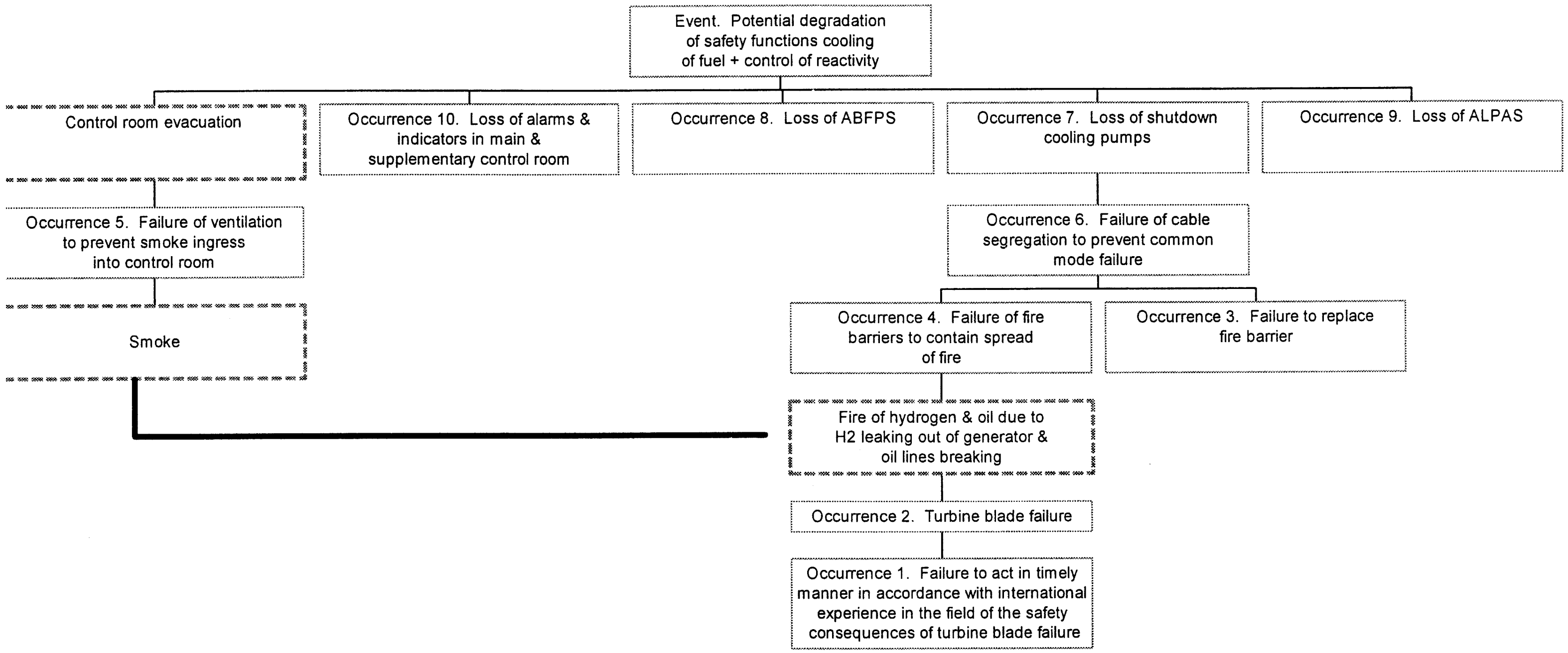

FIG. I.1. Logic tree of occurrences for reference plant 1.

Several systems necessary for monitoring and maintaining the reactor of Unit 1 in safe shutdown condition were repaired to the required functional level.

Prior to the event, line, transformer and generator (LTG) panels of Unit 2 were in the Unit 1 control equipment room. These have been relocated to the Unit 2 control equipment room. In Unit 2 cable re-routing has been carried out so that the possibility of common cause failure is eliminated. The turbine rotor in Unit 2 has been replaced by a new rotor which has a modified design of LP 5th stage blades (the stage which failed in the original turbine failure).

In response to the event, utility management decided to sequentially shut down each operating PHWR station (having TG sets supplied by the same manufacturer) for thorough inspection of the turbines, generators and their associated components.

I.8. GENERIC LESSONS

After in-depth examination of various issues, some of the important lessons which have been learnt are shown below. *Note: these include issues which are relevant to the full event which are not necessarily described in the preceding sections.*

1. There is a need to strengthen the quality assurance (QA) at all stages (design, installation, commissioning and operation).
2. The design of the fire barriers needs to be thoroughly reviewed for their adequacy to meet fire safety requirements. The fire barriers need to be tested and qualified before installation in position.
3. Adequate quality control needs to be exercised while doing maintenance work on fire barriers/cables, so that their replacement in position is ensured before leaving the workplace.
4. In-depth review of physical separation and fire protection provisions for power and control cables should be carried out to guard against common mode failure such as fire.
5. Control room habitability should be ensured under adverse external conditions through adequate provision in the ventilation system.
6. The capability to handle extended station blackout condition (with class I and II power supply also not available) should be reviewed along with the duration of the station blackout.
7. Pre-service and in-service inspection of TGs should be strengthened. Operating procedures should be adhered to.
8. There is a need for a detailed design safety review of the systems outside the nuclear steam supply system which have the potential of affecting reactor safety.
9. The adequacy and reliability of supply of water from fire fighting system to cater for the simultaneous needs of fire fighting and supply to steam generators and other safety related equipment should be investigated.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 1, OCCURRENCE 3	ASSET
Event title:	Potential degradation of safety function "cooling of fuel" & "control of reactivity" , due to loss of electrical power, control and instrumentation cables, and loss of main control room habitability due to smoke ingress as a result of a major fire in the turbine hall	Safety consequences due to initiating failure
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**		Corrective actions by plant
Occurrence title:	Maintenance/modifications failed to replace fire barriers	

					Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
Nature of the failure	X	Personnel failure	Occurrence results from a failure during operation	X						
		Equipment failure	Occurrence results from a deficiency discovered by periodic testing							
		Procedure failure								

			Yes	No	Yes	No	Yes	No
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**		**How to eliminate the problem?** **(Corrective actions by ASSET method)**						
Latent weakness of the element that failed to perform as expected	Failure on the part of maintenance to appreciate the safety implications of non-replacement of fire barriers	**I** Maintenance chief to review the safety issues & awareness with the maintenance personnel & to establish a sound safety culture within the team						
Contributor to the existence of the latent weakness: Not qualified prior to operation. Poor quality control: Qualification degraded during operation. Poor preventive maintenance: X	The sense of awareness of safety issues had eroded	**II** Training engineer to review training and qualification of maintenance staff in the field of safety awareness						
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**		**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness: Detection: X Restoration:	Surveillance by the supervisor of the performance of staff failed to detect the weakness in the maintenance staff	**III** Training manager to review training and arrange training for all supervisors regarding their role in observing staff performance and attitudes concerning safety						
Contributor to the existence of the deficiency Inadequate policy for: Surveillance: X Feedback:	Inadequate application of plant policies aimed at safety awareness.	**IV** Station management to review policy & its application across all disciplines						

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. I.2. Event root cause analysis form: reference plant 1, occurrence 3.

IAEA		**EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 1, OCCURRENCE 4**		**ASSET**					
Event title:		Potential degradation of safety function “cooling of fuel” & “control of reactivity”, due to loss of electrical power, control and instrumentation cables, and loss of main control room habitability due to smoke ingress as a result of a major fire in the turbine hall”		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: OCCURRENCE: What failed to perform as expected?				Corrective actions by plant					
Occurrence title:		Fire barriers failed to contain spread of fire							
Nature of the failure		Personnel failure	Occurrence results from a failure during operation X	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
	X	Equipment failure	Occurrence results from a deficiency discovered by Periodic testing						
		Procedure failure							
SAFETY PROBLEMS: DIRECT CAUSE: Why did it happen?			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		Fire barrier material was inadequate to stand high thermal gradients caused due to fire	**I** Design department to select a more suitable material and arrange qualification tests before applying to service						
Contributor to the existence of the latent weakness:		No pre-service qualification tests had been carried out.	**II** Design department to specify appropriate tests and acceptance criteria for selection of new material						
Not qualified prior to operation. Poor quality control	X								
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: ROOT CAUSE: Why was it not prevented?			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		Fire protection surveillance programme failed to detect presence of unqualified barrier material	**III** Director (Eng.) to review scope and content of surveillance programme						
Detection	X								
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		Inadequate policy for the control of materials and equipment used in fire protective/confinement applications	**IV** Director (Eng.) to review policies and management controls in the field of fire protection						
Surveillance	X								
Feedback									

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. I.3. Event root cause analysis form: reference plant 1, occurrence 4.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 1, OCCURRENCE 6		ASSET					
Event title:	Potential degradation of safety function “cooling of fuel” & “control of reactivity” , due to loss of electrical power, control and instrumentation cables, and loss of main control room habitability due to smoke ingress as a result of a major fire in the turbine hall		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**			Corrective actions by plant					
Occurrence title:	Cable segregation failed to prevent common mode failure.							
Nature of the failure	Personnel failure	Occurrence results from a failure during operation: X	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
	Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
	X Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**		**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected	Inadequate segregation & separation of cables.	**I** Design department to revise cable routes and layout						
Contributor to the existence of the latent weakness: Not qualified prior to operation. Poor quality control: X Qualification degraded during operation. Poor preventive maintenance:	Inadequate appreciation at design stage of importance of segregation	**II** Director (Eng.) to initiate design review with reference to the safety issues involved						
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**		**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness: Detection: Restoration: X	Known deficiency remained uncorrected	**III** Station management to reassess prioritization of outstanding safety related issues						
Contributor to the existence of the deficiency Inadequate policy for: Surveillance: Feedback: X	Policy for action upon feed back to reassess prioritization was inadequate	**IV** Station management to review policy & application in the field of safety and experience feedback						

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. I.4. Event root cause analysis form: reference plant 1, occurrence 6.

Annex II

REFERENCE PLANT 2

II.1. EVENT DESCRIPTION (NARRATIVE)

Reference plant 2 is the second unit of a four-unit RBMK type NPP.

Initial status of the plant

The plant was in the process of startup following a two month shutdown period. During this process, a steam leak was discovered which necessitated the temporary shutdown of turbogenerator no. 4.

The reactor was at a power level of 1570 MW(th). The turbogenerator No. 3 was at 425 MW(e) with turbogenerator No. 4 at no load.

Other significant plant items in service included:

– Main feedwater pumps 4 and 5.

– Main circulating pumps 12, 13, 14 and 22, 23, 24.

Detection of the event

At 20:10 on 11 October 1991, during a planned shutdown of turbogenerator 4 (TG4), the operator in the central control room (CCR) discovered that the breaker BII-11-330 was switched on; the operators in the unit control room (UCR) and the operators in CCR felt the noticeable vibration of the whole building and serious vibrations of TG4. Almost at the same time, they discovered the fire in the turbine hall of TG4.

Brief description of the event

At 19:46 on 11 October 1991, TG4 was decoupled from the grid by breakers BII-11-330-4GT with the agreement of the dispatcher in Kiev. A further request for permission to open isolator TP-4GT was also granted. The CCR instructed the field operator to check the position of the breakers and to open the isolator TP-4GT. The field operator had to walk 150 m to verify the position of the breakers before he could open the isolator. The event took place before he could fulfil this task.

At 20:10, the speed of TG4 was about 50 rpm. Accidental closure of the breaker BII-11-330 caused TG4 to operate as an asynchronous motor. As a result of significant vibrations and consequent rotor displacement, leakage and then combustion of the generator hydrogen and oil occurred. The operator in UCR initiated the manual trip of the reactor.

Due to the lack of any smoke discharge facilities and insufficient cooling of the steel structure, the roof collapsed, falling over TG4, the main feedwater pumps, the emergency feedwater pumps, and their control boards. As a result, TG4 and its exciter were damaged, three (of five) main feedwater pumps and one (of three) emergency feedwater pumps were damaged. Later attempts to provide emergency feedwater failed due to low pressure in the discharge line. One main feedwater pump, however, could be started, but had to be stopped again when, after some minutes, water in the steam drum separator (SDS) reached a high level. Eventually the entire feedwater supply was disabled because the electrical supply to these systems was switched off according to fire fighting procedures. The reactor cooling function and water inventory replenishment was then maintained by increased injection of seal water to the main circulating pumps. When the reactor pressure had dropped below 12 bar, the injection of water was activated from the clean condenser storage tanks by the clean condenser supply pumps through the main and emergency feedwater pumps.

During the event, four feedwater pumps out of five were lost due to loss of control of their motors and the discharge isolating valves. The last main feedwater pump was tripped by an operator when the water level in the SDS became too high.

Independently of the fire, control of a steam dump valve was lost owing to a partially stuck open position, causing a fall in the water level in the SDS. The injection of cold water from the clean condenser pump also contributed to the drop in this level during a short period. It is important to note that the proper actions taken by the operators based on their knowledge and experience enabled core cooling to be maintained throughout the event.

As soon as the fire was discovered, the fire brigades were activated, and the plant staff started fire fighting within five minutes. The fire took three and a half hours to contain. At 23:58, the reactor was in a safe mode, the decay heat removal was under control and normal procedure for cold shutdown established. The fire was extinguished at 02:20 on October 12, 1991.

During the event, TG3 (the undamaged turbogenerator of Unit 2) was discovered to be connected to the grid after shutoff of its steam supply. It was running as a synchronous motor at 3000 rpm for close to 20 minutes without any obvious adverse consequences. At the end of these 20 minutes it was shut off by the operator.

Final status of the plant

The fire was extinguished and Unit 2 was in cold shutdown mode. Unit 1 was still in operation. TG5 of Unit 3 (close to TG4) was shut down.

Actual consequences of the event

Off-site impact: none.

On-site impact:

- Impact on personnel: none.
- Impact on plant safety functions performance: the core cooling function was severely degraded due to the loss of the emergency and main feedwater systems and the loss of control of water inventory in the recirculation circuit.
- Impact on plant structures: as a result of the fire, one of the three emergency feedwater pumps was damaged as well as one of five main feedwater pumps. Part of the turbine hall roof and equipment in the turbine hall in the vicinity of TG4 was destroyed or damaged.

Degradation of defence in depth

- Degradation of the safety function “BARRIER” (passive features): none.

- Degradation of the safety function “PROTECTION” (active features): the core cooling capability was degraded.
- Degradation of the safety function “SUPPLY”: a part of the auxiliary electrical power supply and the local control panels and cubicles of emergency feedwater were lost.

Immediate actions taken

The following actions were immediately taken:

- Activation of fire brigades
- Fire fighting by plant staff
- Manual trip of reactor and turbogenerator TG3
- Emergency draining of lubricating oil
- Depressurisation of generator casing (H_2) of TG3 and TG4 by purging with N_2.

The following actions were immediately taken to restore the plant safety:

- Manual reactor trip
- Initiating rapid reactor cold shutdown procedure

Item	Time	EVENT
1.	19:46	Planned trip of turbogenerator No. 4. The turbine stop-control valves were closed followed by the opening of generator circuit breakers. The remote isolator between the main transformer and the circuit breakers was not immediately opened.
2.	20:10	Turbogenerator No. 4 was at approximately 50 rpm when Generator Circuit Breaker BII-11-330 accidentally closed, causing the turbogenerator to run up to full speed in about 30 seconds as an asynchronous motor. Severe vibration could be felt throughout the building and a fire occurred in the vicinity of the alternator. **Comment:** The closure of the generator circuit breaker was caused by a short circuit between two wires in a control cable between the control room and the circuit breaker. The cause of the vibrations was the overheating of the alternator rotor and resulting damage to the rotor windings. Displacement of the rotor windings produced out of balance forces during the acceleration of the rotor up to full speed.
3.	20:10:40	A three-phase short circuit occurred on the generator stator bus-bars. The generator protection system was actuated and opened the generator circuit breaker, thereby overriding the remaining closing signal caused by the short circuit in the control cable. However, the circuit breaker re-closed immediately due to this closing signal. The off-on action of the breaker was operated on once more. The fault was eventually cleared when the circuit breaker at the end of the grid line (200 km away) was opened by

the grid protection system. This finally left the turbogenerator disconnected from the grid.

Comment: The turbogenerator is not provided with reverse power protection. The repeated actions of the air-blast circuit breaker continued until the air pressure was insufficient to allow further action. The total time elapsed from the short circuit on the alternator bus-bars and turbo-generator disconnection was 1.18 s.

4. 20:10:52 Manual trip of the reactor and turbogenerator No. 3 (TG3)

Comment: The generator circuit breakers of turbogenerator No. 3 were left closed with the generator excitated until 20:32. *NOTE*: The turbogenerator remained at 3000 rpm and acted as an asynchronous motor without suffering any observable damage. At this stage the vacuum was broken on both main condensers and they were therefore not available as heat sinks.

5. 20:11 Fire brigade called.

6. 20:13 Control room shift supervisor ordered cooldown of the reactor at a rate of 30^{o}C/hr using the steam dump valve discharging to the steam suppression tank.

Comment: The intention was to reach cold shutdown as quickly as possible in accordance with the technical specifications.

7. 20:14 The operator tripped one of the two engaged main feedwater pumps.

Comment: One main feedwater pump remained in service.

8. 20:16 Fire brigade arrived at the fire.

9. 20:18 Turbogenerator lubricating oil pumps were manually tripped and manual draining of the lubricating oil tank commenced.

Comment: The oil was drained to tanks located outside the turbine building. These tanks were however partially filled resulting in oil spillage onto the surrounding floor area but not in the immediate vicinity of the fire.

10. 20:20 Trip of the only remaining engaged main feedwater pump due to high water level in the SDS.
Comment: The cause of the high water level was the failure of the main feedwater pump discharge valve to close partly, combined with a designed minimum leakage flow through the control valves.

11. 20:23 Fire brigades given permission to start fire fighting.

12. 20:24 Roof collapsed over turbogenerator No. 4 and feedwater pumps.

Comment: Attempts to cool the roof structure were unsuccessful due to low pressure in the feedwater system to the fire hoses (hose spray could not reach roof structures).

13. 20:38 Failure of the Steam Dump Valve (SDV) accompanied by falling water level in the SDS.

Comment: The SDV was stuck in a partially open position due to a mechanical deficiency.

14. 20:40 Loss of control of main feedwater pumps 2, 3 and 4 and their associated flow control valves.

Comment: Damage from fire and roof collapse.

15. 21:00 Water level in SDS below the emergency set point.

Comment: No feedwater pumps (main or emergency) were in service at this time. Too much steam was discharged through the SDV, which was not controllable.

16. 21:15 Attempts to establish emergency feedflow failed, but main feedwater pump No. 1 started.

Comment: One emergency feedwater pump failed to start, while another was started and then tripped by the operator due to low pressure in the discharge line and based on information about a pipe leakage in the area of emergency feedwater pumps.

17. 21:20 The feedwater pump No. 1 was tripped by the operator.

Comment: The reason for tripping was the same as in item 10: high water level in the SDS.

18. 21:40 Operator disconnected the electrical supply to all mains and emergency feedwater pumps.

Comment: In order to enable fire fighting in the vicinity of electrical equipment.

19. 22:10 Make-up to the re-circulation circuit was provided via the seal water supply to the main circulating pumps from the condenser system.
Comment: Quantity of make-up water injected uncertain.

20. 23:03 Water level in both the left and right SDSs fell to below the measurable range.

Comment: Operator action was based on the performance of the main circulating pumps, i.e. they should not cavitate when in operation. The reactor pressure had decreased to the level where low pressure feedwater injection from the clean condenser storage tank could be actuated. The low temperature of the feedwater caused the SDS water level to drop during a short time.

21.	23:15	Water level in the right SDS increased to measurable range.
22.	23:41	The fire was under control.
23.	23:45	Water level in the left SDS increased to measurable range.
24.	23:58	Normal water level restored in both SDSs.
25.	02:20	Fire declared to be extinguished.

II.2. EVENT TITLE

Degradation of core cooling due to fire in turbine hall.

II.3. CHRONOLOGICAL LIST OF OCCURRENCES

Occurrence 1:	Procedure fails to give guidance to minimize risk.
Occurrence 2:	Operation fails to open the isolation in time.
Occurrence 3:	Control cable fails to provide signal.
Occurrence 4:	Circuit breaker fails to maintain open position.
Occurrence 5:	Hydrogen and oil seals fail to be leaktight.
Occurrence 6:	Ventilation system fails to remove smoke.
Occurrence 7:	Fire suppression system fails to deliver sufficient water at desired pressure.
Occurrence 8:	Structural supports for the roof fail.
Occurrence 9:	Emergency feedwater system fails to be resistant to impact of fire, water and falling roof.
Occurrence 10.	Water level in the SDS below the indicator measurement capability.
Occurrence 11:	Steam dump valve fails to close.

II.4. LOGIC TREE OF OCCURRENCES

The logic tree of occurrences of the above mentioned event is shown in Fig. II.1.

II.5.SELECTION OF OCCURRENCES TO BE ANALYSED

Occurrence 1: Procedure fails to give guidance to minimize risk. This occurrence is of significance in that the procedure did not stress or explain the urgency needed in opening the local isolator.

Occurrence 3: Control cable fails to provide the right signal. This occurrence is of high significance in that the breaker BII-11-330 was accidentally switched on leading to the acceleration of TG4 and the functioning of generator No. 4 as an asynchronous motor.

Occurrence 7: Fire suppression system fails to deliver sufficient water at the desired pressure. This occurrence is selected to be analysed because of its high significance in the event. The most important aspect of this occurrence was that the roof structure could not be adequately cooled and collapsed over TG4, redundant trains of emergency feedwater pumps and control panels.

Occurrence 9: Emergency feedwater system fails to be resistant to impact of fire, water and falling roof. This occurrence is of high significance because the pumps are essential for maintaining the core cooling function (water inventory).

Occurrence 11: Steam dump valve fails to close. This occurrence is of high significance in supporting the core cooling function.

II.6. ROOT CAUSE ANALYSIS OF SELECTED OCCURRENCES

Figures II.2–II.6 show the root cause analysis forms for the occurrences selected in Section II.5.

II.7. CORRECTIVE ACTIONS

Ukrainian experts have been charged with identifying the safe shutdown equipment located in the turbine hall. Improvements will be made to protect the safe shutdown equipment from the effects of fire. Other utility operators have been provided with the lessons learned from this event and should make similar improvements.

II.8. GENERIC LESSONS

The analysis has highlighted the need to improve safety culture, in particular the lack of awareness on the part of various disciplines as to fire safety. This points to the need for the urgent training of personnel at various levels with a view to maintaining better standards of safety culture amongst all personnel.

The incident also brings out the need for implementing without delay the feedback of experience from internal and external sources by the plant management to ensure that these identify clearly the safety implications of the various tasks performed by the respective groups. Significant incidents need to be analysed for their root causes in order to clearly point out the weaknesses in the existing practices and corrective actions taken to prevent the recurrence of such incidents. The intention is not to blame individuals or groups for the incidents, but to indicate possible erosion in safety awareness which needs to be corrected on a practical basis.

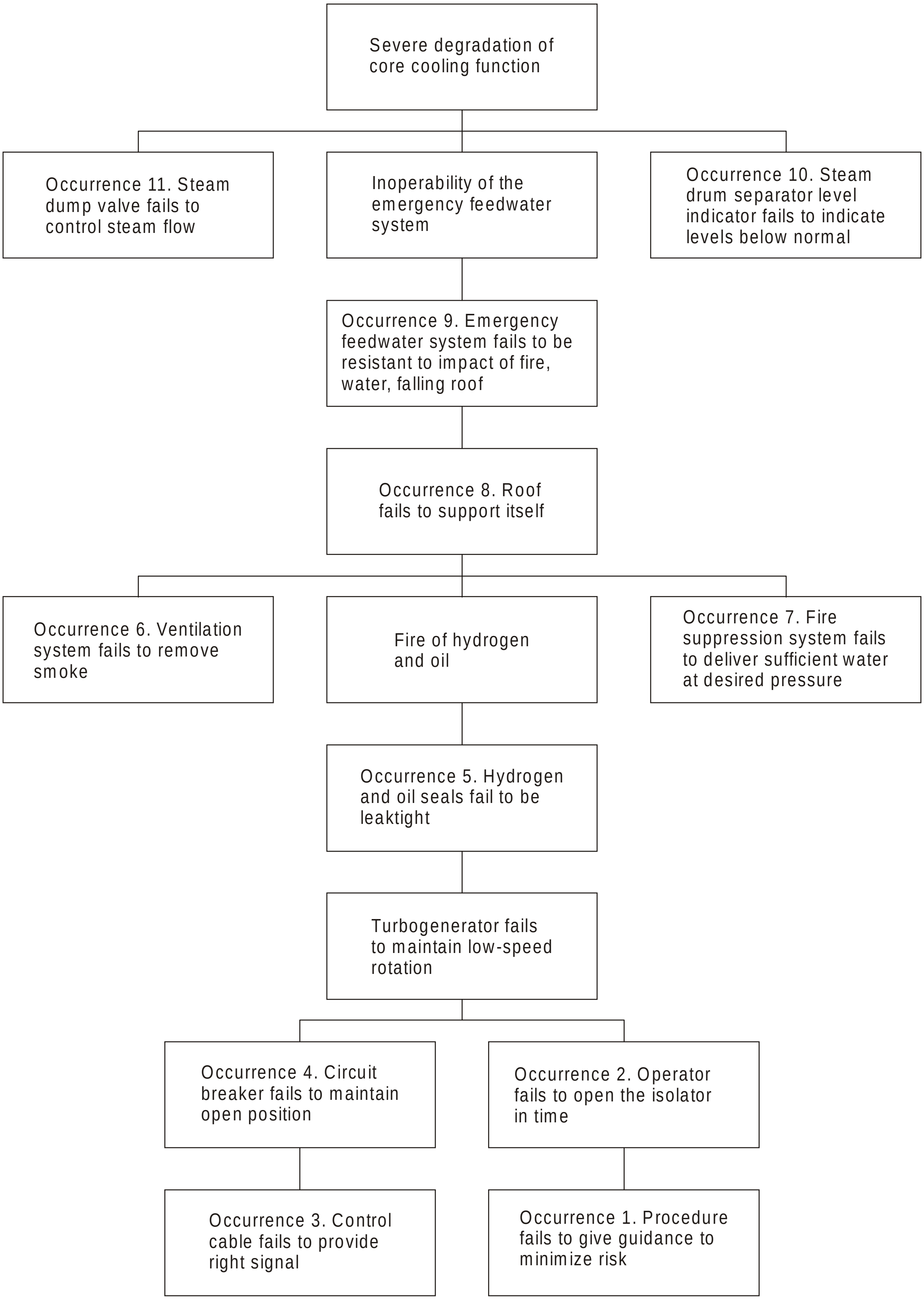

FIG. II.1. Establishment of the logic tree of occurrences.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 2, OCCURRENCE 1			ASSET					
Event title:	Degradation of core cooling system due to fire in the turbine hall			Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title:	Procedure failed to give guidance to minimize risk								
Nature of the failure		Personnel failure	Occurrence results from a failure during operation	X	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed
		Equipment failure	Occurrence results from a deficiency discovered by Periodic testing						
	X	Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**		Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		No detailed guidance given for disconnection and isolation of T/G from grid to ensure prompt isolation from the grid	**I** Revise and update procedure – operations manager and electrical engineer.						
Contributor to the existence of the latent weakness:		Procedure not validated and contained other omissions, such as the need to report back to control room upon completion of isolation	**II** Operations manager to independently review scope and accuracy of new procedure						
Not qualified prior to operation. Poor quality control	X								
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		No surveillance programme was available to ensure systematic review and updating of procedures with the involvement of operating personnel.	**III** Plant senior management to organize systematic review of procedures, involving staff concerned on the basis of an on-going programme.						
Detection	X								
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		Management policy does not facilitate action on lessons learned from previous events and their translation into procedural changes	**IV** Station manager to evolve policy directions in the fields of operational feedback from internal & external sources						
Surveillance									
Feedback	X								

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. II.2. Event root cause analysis form: reference plant 2, occurrence 1.

<table>
<tr><td colspan="2">IAEA</td><td colspan="4">EVENT ROOT CAUSE ANALYSIS FORM
EXAMPLE: REFERENCE PLANT 2, OCCURRENCE 3</td><td colspan="6">ASSET</td></tr>
<tr><td colspan="2">Event title:</td><td colspan="4">Degradation of core cooling system due to fire in the turbine hall</td><td colspan="6">Safety consequences due to initiating failure</td></tr>
<tr><td colspan="6">SAFETY PERFORMANCE:
OCCURRENCE: What failed to perform as expected?</td><td colspan="6" rowspan="2">Corrective actions
by plant</td></tr>
<tr><td colspan="2">Occurrence title:</td><td colspan="4">Control cable
failed to provide the right signal</td></tr>
<tr><td colspan="2" rowspan="3">Nature of the failure</td><td></td><td>Personnel failure</td><td>Occurrence results from a failure during operation</td><td>X</td><td colspan="2" rowspan="3">Ap-pro-pri-ate</td><td colspan="2" rowspan="3">Com-pre-hen-sive</td><td colspan="2" rowspan="3">Im-ple-ment-ed</td></tr>
<tr><td>X</td><td>Equipment failure</td><td rowspan="2">Occurrence results from a deficiency discovered by Periodic testing</td><td rowspan="2"></td></tr>
<tr><td></td><td>Procedure failure</td></tr>
<tr><td colspan="4">SAFETY PROBLEMS:
DIRECT CAUSE: Why did it happen?</td><td colspan="2">How to eliminate the problem?
(Corrective actions by ASSET method)</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">Latent weakness of the element that failed to perform as expected</td><td colspan="2">Damage occurred during installation caused loss of integrity of conductor insulation</td><td colspan="2">I Comprehensive testing of all similar cables to eliminate potential future failures</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Contributor to
the existence of the latent weakness:</td><td colspan="2" rowspan="3">Inadequate quality control of cable installation and working methods</td><td colspan="2" rowspan="3">II Engineering manager to arrange appropriate quality assurance for new/replacement cable installation</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Not qualified prior to operation. Poor quality control</td><td>X</td></tr>
<tr><td>Qualification degraded during operation. Poor preventive maintenance</td><td></td></tr>
<tr><td colspan="4">SAFETY CULTURE:
ROOT CAUSE: Why was it not prevented?</td><td colspan="2">How to prevent recurrence?
(Corrective actions by ASSET method)</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td colspan="2">Deficiency in timely eliminating the latent weakness:</td><td colspan="2" rowspan="3">Existing surveillance programme of a meggar test once every 3 years was inadequate to detect developing latent weaknesses of insulation</td><td colspan="2" rowspan="3">III Engineering manager and cable specialist to identify appropriate testing techniques & surveillance programme requirements</td></tr>
<tr><td>Detection</td><td>X</td></tr>
<tr><td>Restoration</td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the deficiency

Inadequate policy for:</td><td colspan="2" rowspan="3">A similar failure of a breaker due to damage of the control cable lines had occurred earlier. This event was the precursor of the present incident and should have prompted all such cables to be thoroughly tested. Manage-ment policy, however, did not include an adequate detection programme</td><td colspan="2" rowspan="3">IV Station manager to review policy and arrangements for recognizing and incorporating lessons learned from operational experience within & outside of the plant</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Surveillance</td><td></td></tr>
<tr><td>Feedback</td><td>X</td></tr>
</table>

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. II.3. Event root cause analysis form: reference plant 2, occurrence 3.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 2, OCCURRENCE 7				ASSET					
Event title:	Degradation of core cooling system due to fire in the turbine hall				Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**					Corrective actions by plant					
Occurrence title:	Fire suppression system failed to deliver sufficient water at the desired pressure									
Nature of the failure	X	Personnel failure	Occurrence results from a failure during operation	X	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
		Equipment failure	Occurrence results from a deficiency discovered by Periodic testing							
		Procedure failure								
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**		Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected	Inadequate capacity of the fire suppression system to control turbogenerator fire of the size experienced during this event		**I** Review system design taking into account assessment of duty requirements							
Contributor to the existence of the latent weakness:	Identification of fire hazards prior to operation was inadequate because it lacked a detailed analysis of needed capacity		**II** Perform a detailed analysis of the fire potential and install fire suppression system capable of controlling fires							
Not qualified prior to operation. Poor quality control	X									
Qualification degraded during operation. Poor preventive maintenance										
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**							
Deficiency in timely eliminating the latent weakness:	Surveillance programme failed to perform periodic reviews of the fire protection requirements and the capability of the installed fire suppression system		**III** Review scope & application of surveillance programme with respect to fire hazards and installed fire suppression system							
Detection	X									
Restoration										
Contributor to the existence of the deficiency Inadequate policy for:	Plant policy did not give adequate direction for surveillance in respect of fire suppression system		**IV** Station management to review policy in the field of surveillance of fire suppression system							
Surveillance	X									
Feedback										

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. II.4. Event root cause analysis form: reference plant 2, occurrence 7.

<table>
<tr><td colspan="2">IAEA</td><td colspan="4">EVENT ROOT CAUSE ANALYSIS FORM
EXAMPLE REFERENCE PLANT 2: OCCURRENCE 9</td><td colspan="6">ASSET</td></tr>
<tr><td colspan="2">Event title:</td><td colspan="4">Degradation of core cooling system due to fire in the turbine hall</td><td colspan="6">Safety consequences due to initiating failure</td></tr>
<tr><td colspan="6">SAFETY PERFORMANCE:
OCCURRENCE: What failed to perform as expected?</td><td colspan="6" rowspan="2">Corrective actions by plant</td></tr>
<tr><td colspan="2">Occurrence title:</td><td colspan="4">Emergency feedwater system
failed to be resistant to impact of fire, water & falling roof</td></tr>
<tr><td colspan="2" rowspan="3">Nature of the failure</td><td>X</td><td>Personnel failure</td><td>Occurrence results from a failure during operation</td><td>X</td><td colspan="2" rowspan="3">Ap-pro-pri-ate</td><td colspan="2" rowspan="3">Com-pre-hen-sive</td><td colspan="2" rowspan="3">Im-ple-ment-ed</td></tr>
<tr><td></td><td>Equipment failure</td><td rowspan="2">Occurrence results from a deficiency discovered by periodic testing</td><td rowspan="2"></td></tr>
<tr><td></td><td>Procedure failure</td></tr>
<tr><td colspan="4">SAFETY PROBLEMS:
DIRECT CAUSE: Why did it happen?</td><td colspan="2">How to eliminate the problem?
(Corrective actions by ASSET method)</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">Latent weakness of the element that failed to perform as expected</td><td colspan="2">Original design was insufficient to provide protection of the equipment against common cause failures like flooding or fire (e.g. segregation, waterproof covers)</td><td colspan="2">I Identified latent weaknesses should be eliminated following a comprehensive, prioritized pro–gramme</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the latent weakness:</td><td colspan="2" rowspan="3">Failure to identify the vulnerability of the emergency feedwater system to impact of fire, water and mechanical damage. Impacts were not recognized when quality was controlled prior to operation</td><td colspan="2" rowspan="3">II Design criteria should be reviewed in the light of current knowledge and international operating experience</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Not qualified prior to operation. Poor quality control</td><td>X</td></tr>
<tr><td>Qualification degraded during operation. Poor preventive maintenance</td><td></td></tr>
<tr><td colspan="4">SAFETY CULTURE:
ROOT CAUSE: Why was it not prevented?</td><td colspan="2">How to prevent recurrence?
(Corrective actions by ASSET method)</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td colspan="2">Deficiency in timely eliminating the latent weakness:</td><td colspan="2" rowspan="3">The surveillance programme did not include a summary of the acceptance criteria for the vulnerability of the emergency feedwater system</td><td colspan="2" rowspan="3">III The surveillance program should be reviewed to include acceptance criteria applicable to all safety related systems</td></tr>
<tr><td>Detection</td><td>X</td></tr>
<tr><td>Restoration</td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the deficiency

Inadequate policy for:</td><td colspan="2" rowspan="3">The surveillance policy did not include an adequate feedback system to implement the lessons learned from other plants: big fires with high potential safety significance due to common mode failures already occurred in other plants such as Greifswald, Germany 1975, Beloyarsk, Russia 1978 or Armenia 1982</td><td colspan="2" rowspan="3">IV Station management should review the policy & its application with particular attention to capitalizing on operating experience and lessons learned within the plant and elsewhere</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Surveillance</td><td></td></tr>
<tr><td>Feedback</td><td>X</td></tr>
</table>

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. II.5. Event root cause analysis form: reference plant 2, occurrence 9.

IAEA		**EVENT ROOT CAUSE ANALYSIS FORM** **EXAMPLE: REFERENCE PLANT 2, OCCURRENCE 11**		**ASSET**					
Event title:		Degradation of core cooling system due to fire in turbine hall		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title:		Steam dump valve failed to close							
Nature of the failure		Personnel failure	Occurrence results from a failure during operation: X	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
	X	Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		Defective arrangements for gland packing on hand wheel shaft led to stalling of actuator motor	**I** Review design material used and maintenance procedures to eliminate problem.						
Contributor to the existence of the latent weakness:		Although quality control on safety related equipment was applied to the valve, there were no written acceptance criteria	**II** Engineering manager to determine acceptance criteria to be applied in all cases.						
Not qualified prior to operation. Poor quality control	X								
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		Inadequate surveillance programme. Weekly visual checks were required by field operator but no procedures or checklists defining the inspection. There was no written report from the field operator showing what had been done and what the results of such actions were	**III** Improve surveillance programme by 1) using inspection procedures de–fining actions and related acceptance criteria; 2) issuing a clear statement from management regarding import–ance of and attention to be given to small directions						
Detection									
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		Management policy for sur-veillance and its application were inadequate to ensure timely elimination of latent weakness which was	**IV** Include in feedback program the analysis of potential safety significance of latent weaknesses observed on safety related equipment and prioritize corrective & preventive actions accordingly						
Surveillance		to staff & management							
Feedback		from previous experience							

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. II.6. Event root cause analysis form: reference plant 2, occurrence 11.

Annex III

REFERENCE PLANT 3

III.1. EVENT DESCRIPTION (NARRATIVE)

Reference plant 3 is one unit of a two unit pressurized water reactor (PWR) type NPP with a designed electrical power of 1200 MW(e).

Initial status of the plant

The unit was starting up after the annual refuelling outage and maintenance period. The reactor was still in shutdown condition, but the four main coolant pumps (MCP) were running to heat up primary and secondary circuit (primary temperature: 282^{o}C, pressure: 15.5 MPa).

Brief description of the event

At 16:04 on 4 March 1994, the unit was still under shutdown conditions (0 MW) while the four main coolant pumps were running to heat up the primary and secondary circuits. A signal "10BZ00 U203XU01 ground fault (short to ground) BA/BB/BC/BD" was enunciated. Thirty five minutes later the automatic fire detection system gave an alarm for the motor of one of the four main coolant pumps (HKP10). The shift fire fighting personnel could not observe any fire signals. Three minutes later the respective MCP tripped by a short circuit. The firemen took the lubrication oil supply system out of operation and prepared manually the spraywater deluge system for actuation. Nevertheless, no flames were visible. Fifty eight minutes after the first alarm signal, flames and smoke became observable, so that the fire fighting could be started, and the fire alarm had to be signalled. The spraywater deluge system was actuated manually from the unit control room. Seventy seven minutes after the ground circuit signal, the fire was successfully extinguished.

The following damages due to the fire were found:

– damage to fire detector No. 1 of the detection line No. 17, directly adjacent to the stator due to temperature effects, the detector including its cable had to be exchanged;
– bottom part of the motor hood affected by soot, no effects/signs of fire visible on top of the hood;
– no further observations, in particular no deterioration found at the cables of the redundant trains 1 and 3 being installed on a cable tray at a distance of 2.5 m from the motor.

The fire was limited to parts of the MCP motor. Safety related equipment was neither affected by the fire itself nor by the fire extinguishing measures.

At 17:24 on 4 March 1994, one hour and 20 minutes after the start of the event, the spraywater system was taken out of operation, the plant was kept under shutdown condition (0 MW) to be restarted again after detailed analysis of the event.

The detailed event sequence was the following:

16:04 Signal at the unit control room: "ground fault in the 10 kV normal power supply"; this ground fault concerns one of the four 10 kV house load bus-bars together with the respective emergency bus-bar. The affected 10 kV bus-bar is

	connected both to the MCP motor as to other pumps with power output of more than 550 kW. The experts from the responsible department start clarifying the causes. They open and close electrical connections to find out where the ground fault occurred.
16:39	One fire detector (optical smoke detector) of the detection line No. 17 detects smoke, causing the “fire alarm room 1423 motor of MCP” signal to be announced to the unit control room. As a result, the video camera for room 1423 is connected to a monitor in the unit control room.
16:40	Signal of fire detection line No. 18 in room 1423, further signals from other lines follow. Two firemen of the professional plant internal fire brigade arrive at the respective plant location and try to find out whether or not there is a fire in the area of the actuated fire detection lines. No smoke or fire is observed.
16:42	A short circuit between two phases of the MCP motor results in an automatic MCP trip (by an automatic switch). Signal at the unit control room: “MCP failure”. Another two firemen arrive at the affected plant location, the plant staff does not observe any sign of a fire.
17:02	Flames become visible at 16:39 on the video monitor put into operation for the area of the MCP motor. Immediately before this happens, plant personnel in the affected area detect smoke; due to administrative procedures, the shift personnel signals a level-1 fire alarm, whereby all available professional and non-professional fire fighters are mobilized. Manual fire fighting is started by 13 professional plant internal fire fighters with portable $CO_2$and powder fire extinguishers; the firemen are equipped with pressurized air masks. During fire fighting further re-ignitions occur.
17:03	The shift personnel signals a level-2 fire alarm, whereby all members of the plant internal fire brigade available outside the plant site at the respective time are called on by portable means of communication to come to the plant site. (This is always necessary in accordance with administrative procedures in case of fire in the controlled area.)
17:09	The fire brigade team leader in the unit control room and the shift leader decide to actuate manually the stationary spraywater deluge system for the area of the MCP and additionally to bring two C-type water hoses to the affected area.
17:10	Manual actuation of the stationary spraywater deluge system is begun. At the same time, two C-type water hoses are brought into operation.
17:15	The fire is extinguished successfully, this is controlled at the respective plant area.
17:21	Fire brigade team leader announces to the shift leader: “fire out”.
17:24	The spraywater deluge system is switched off.

After investigation of the MCP motor, a forgotten tool (chisel) was found in the pump.

III.2. EVENT TITLE

The event at reference plant 3 is a non-safety significant and not obligatory reportable event titled “Potential degradation of the safety function cooling the fuel due to damage of the motor of a reactor main coolant pump (MCP)”.

III.3. CHRONOLOGICAL LIST OF OCCURRENCES

The following occurrences can be listed:

Occurrence 1: A worker failed to remove a tool.

Occurrence 2: Procedure failed to provide adequate checks to prevent tools being misplaced.

Occurrence 3: Shift manager failed to assure that all administrative pre-start checks were completed.

Occurrence 4: Control barrier attendant failed to detect tool not brought out of working area.

Occurrence 5: Main coolant pump (MCP) motor failed to trip due to ground fault.

III.4. LOGIC TREE OF OCCURRENCES

Figure III.1 shows the logic tree of occurrences for the above mentioned events.

The following direct causes could be identified for the event:

– Ground fault (short to ground) at the MCP motor due to a tool left behind by a worker:

  The direct cause for the ground fault at the MCP motor was a chisel left behind by the respective worker after maintenance work at the MCP at a place where it was set in motion by mechanical and electrical vibrations, resulting in damage to the isolations. This caused the ground fault between one of the windings and ground, which led to a heating of material and the start of smouldering.

– MCP failure due to short circuit:

  The main reason why the event did not stop with the short circuit was the missing automatic ground fault protection to trip the MCP. The ground fault was not detected immediately, the MCP therefore did not stop and several small sparks occurred. The rapid thermal increase in combination with mechanical damage caused the short circuit of two windings. The MCP motor stopped some 50 seconds after the short circuit occurred. This resulted in boosting the smouldering due to the energy input. The heated air flew upwards and ignited a polyester made figlass material at the upper air inlet of the stator of the MCP motor. These flames then became visible.

The ground fault at the MCP motor is not of high significance, because a small number of equipment items were affected. Had an electrical detection of this ground short taken place, the event would have stopped without causing any fire nor further consequences. Additionally, the loss of the MCP because of a short circuit is not safety significant, as it is considered in the plant design.

III.5. SELECTION OF OCCURRENCES TO BE ANALYSED

Occurrence 1: A worker failed to remove a tool. This occurrence is significant in that the supervision failed to detect deterioration in safety awareness of the contract worker.

Occurrence 2:	The procedures failed to provide adequate checks to prevent tools being misplaced. This occurrence is significant because the policy guidance relating to the surveillance of administrative procedures was inadequate.
Occurrence 3:	The shift manager failed to assure that all administrative pre-start checks were completed. The relevance of this occurrence is the failure of the surveillance over the performance and safety awareness of personnel to detect a latent weakness in the shift manager.
Occurrence 4:	The control barrier attendant failed to detect the tool which had not been retrieved from the working area.
Occurrence 5:	The MCP motor failed to trip due to ground fault. This occurrence is significant in that the surveillance of the safety case failed to detect the potential impact of the electrical protection not designed to trip on a ground fault.

III.6. ROOT CAUSE ANALYSIS OF OCCURRENCES

Figures III.2–III.6 show the forms which summarize the root cause analysis of the aforementioned occurrences.

III.7. CORRECTIVE ACTIONS

The following corrective actions were taken following this event:

– The acceptance criteria for contractor induction training were reviewed and the administrative procedures for barrier control of equipment, materials and tools to be brought temporarily in and out the working area were modified due to the review.

– Furthermore, there were training means arranged to enhance the safety awareness of the shift personnel as well as of the access control personnel to achieve an improved safety culture.

– As a technical measure, the electrical ground fault protection of the MCP was improved in such a way that now an automatic trip of the pump on ground fault is ensured.

III.8. GENERIC LESSONS

Assessment of the event significance and severity

With respect to safety significance, the failure of the main coolant pump (MCP) and the consequences of the fire have to be assessed:

The MCP failure is considered in the plant design and layout. The failure of one MCP during power operation and three loop operation does not cause any risk for the plant, the protection goals are achieved. During hot shutdown conditions, the failure of MCPs is not safety significant.

Consequential damages or deterioration at adjacent parts of the reactor pressure vessel (RPV) or at safety related equipment in the close vicinity were not observed. Therefore, no further safety analyses were carried out. This statement is based on visual inspections (effects on the coloured coatings, visible signs of fire or smoke/soot, etc.) and wiping tests and water analyses with regard to chlorides. The extinguishing water flew downwards to the directly affected area of the respective MCP. The major amount of extinguishing water was collected in the leakage collection ring of the pump and ended up in the sump. The licensee stated that no equipment belonging to the RPV was affected by extinguishing water. The extinguishing water of the plant is taken from wells, it is not taken from the pre-flooding device. The concentration of chloride measured gave values between <0.1 mg/L and 0.5 mg/L, equivalent to those values normally measured in other plant areas. Higher concentrations of 0.2 mg/L to 0.6 mg/L, below the limit of 1 mg/L, were only observed at ten measuring devices in areas not directly in contact with the fire and extinguishing water. A higher chloride concentration due to fire and extinguishing water could not be found.

Furthermore, verifications were made to determine whether short circuit current had caused any deterioration of the electrical power supply of the respective MCP at the RPV boundary. That was not the case.

In conclusion, it can be stated that neither the MCP failure nor the fire caused any safety significant consequences.

It remains to be analysed whether the event sequence could have been more severe under other operational plant conditions. In this context, it must be noted that during power operation the affected areas are not accessible and that a kind of oil film can be released from the motor bearings. In accordance with administrative procedures in case of a fire alarm signal for this area, personnel must ascertain by video camera whether open flames become visible. If this is the case, the stationary fire extinguishing system has to be actuated manually from the control room. This procedure is based on the knowledge that spurious signals may be sent by the automatic fire detection system due to other reasons (e.g. steam leakages). The fire extinguishing systems does not show any deficiencies and should in any case be able to extinguish such a fire successfully. Furthermore, the licensee states that the affected areas are accessible considering the required radiation protection measures after a reactor trip and MCP trip. Manual fire fighting therefore is possible.

Operating experience further shows that at the end of the fuel cycle a very thin oil film without relevance for fire load and spreading can be found on parts of the motor housing which is removed at the beginning of the scheduled refuelling outage. Oil dust potentially to be found in the direct vicinity of the MCP motor is not relevant. It therefore can be stated that the event sequence will not be more severe during power operation.

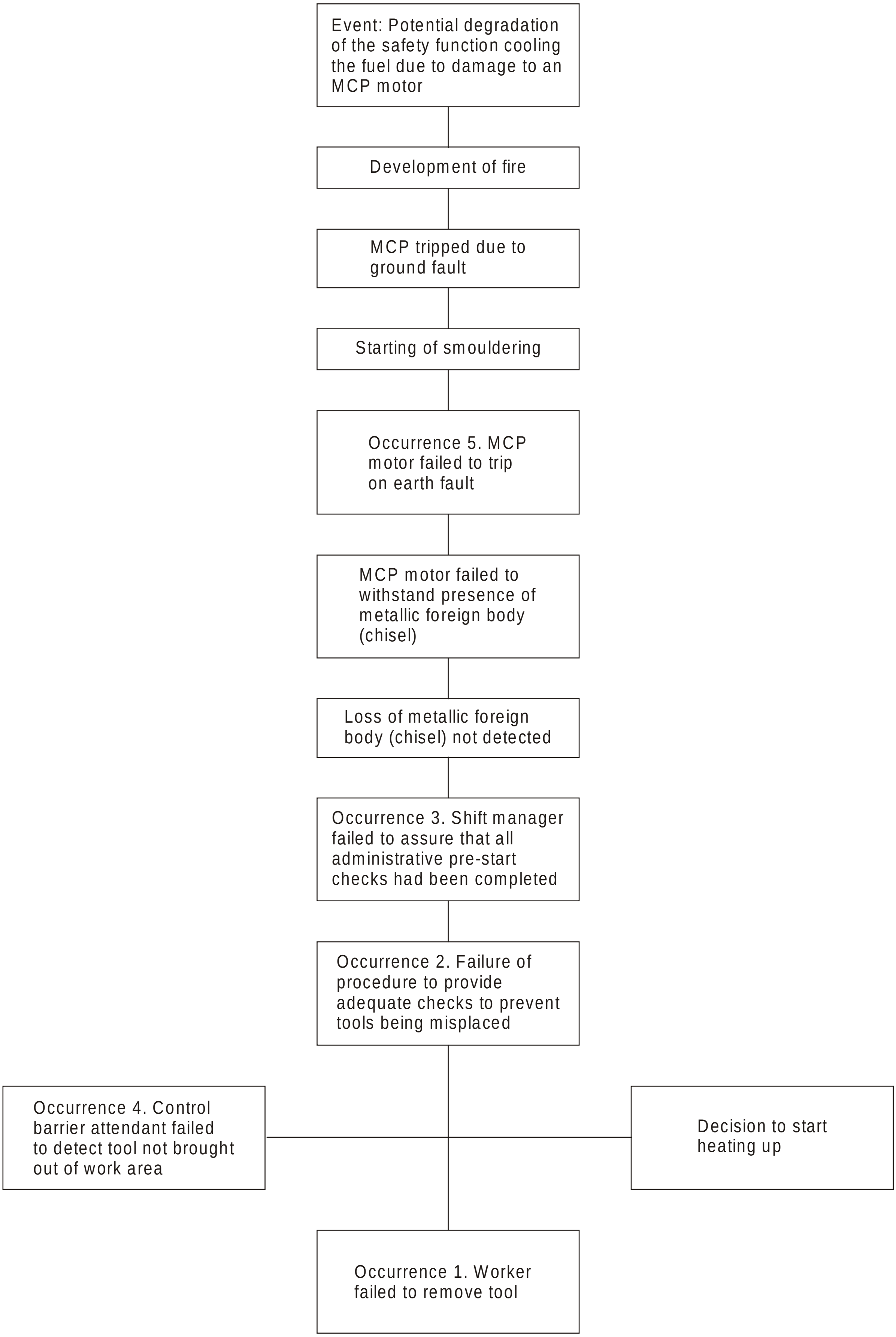

FIG. III.1. Logic tree of occurrences at reference plant 3.

IAEA		**EVENT ROOT CAUSE ANALYSIS FORM** **EXAMPLE: REFERENCE PLANT 3, OCCURRENCE 1**		**ASSET**					
Event title:		Potential degradation of the safety function cooling the fuel due to damage to the motor of a reactor main coolant pump		Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title		Worker failed to remove tool							
Nature of the failure	x	Personnel failure	Occurrence results from a failure during operation — x	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
		Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		Degraded safety awareness of contract worker in that he failed to remove all his tools from workplace in controlled area	**I** Training engineer and contractor supervisor to review acceptance criteria of contractor induction training and the frequency of re-training						
Contributor to the existence of the latent weakness:		Induction training and testing took place prior to the event, the degradation in the worker's safety awareness was not detected	**II** Training engineer to review interval between refresher training.						
Not qualified prior to operation. Poor quality control									
Qualification degraded during operation. Poor preventive maintenance	x								
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:		Supervision failed to detect deterioration in safety awareness of the contract worker	**III** Contractor supervisor (plant staff) to implement surveillance arrangements to detect deterioration in safety awareness of the contract worker						
Detection	x								
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:		The policy guidance relating to the role of supervisors in monitoring the attitude and performance of staff in respect of safety awareness was inadequate	**IV** Station management to review the station policy in monitoring the attitude and performance of staff in respect of safety awareness						
Surveillance	x								
Feedback									

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. III.2. Event root cause analysis form: reference plant 3, occurrence 1.

<table>
<tr><td colspan="2">IAEA</td><td colspan="4">EVENT ROOT CAUSE ANALYSIS FORM
EXAMPLE: REFERENCE PLANT 3, OCCURRENCE 2</td><td colspan="6">ASSET</td></tr>
<tr><td colspan="2">Event title:</td><td colspan="4">Potential degradation of the safety function cooling the fuel due to damage to the motor of a reactor main coolant pump</td><td colspan="6">Safety consequences due to initiating failure</td></tr>
<tr><td colspan="6">SAFETY PERFORMANCE:
OCCURRENCE: What failed to perform as expected?</td><td colspan="6" rowspan="2">Corrective actions
by plant</td></tr>
<tr><td colspan="2">Occurrence title:</td><td colspan="4">Procedure
failed to provide adequate checks to prevent tools being misplaced</td></tr>
<tr><td colspan="2" rowspan="3">Nature of the failure</td><td></td><td>Personnel failure</td><td>Occurrence results from a failure during operation</td><td>x</td><td colspan="2" rowspan="3">Ap-pro-pri-ate</td><td colspan="2" rowspan="3">Com-pre-hen-sive</td><td colspan="2" rowspan="3">Im-ple-ment-ed</td></tr>
<tr><td></td><td>Equipment failure</td><td rowspan="2">Occurrence results from a deficiency discovered by periodic testing</td><td rowspan="2"></td></tr>
<tr><td>x</td><td>Procedure failure</td></tr>
<tr><td colspan="4">SAFETY PROBLEMS:
DIRECT CAUSE: Why did it happen?</td><td colspan="2">How to eliminate the problem?
(Corrective actions by ASSET method)</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">Latent weakness of the element that failed to perform as expected</td><td colspan="2">Procedure was inadequate to ensure that its intended objective (that all tools and equipment be accounted for before clearance for operation) was achieved</td><td colspan="2">I Maintenance manager to review and revise the procedures.</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Contributor to
the existence of the latent weakness:</td><td colspan="2" rowspan="3">Inadequate acceptance criteria for the procedure</td><td colspan="2" rowspan="3">II Operation and maintenance managers to review the administrative checks on work in controlled area. Training engineer to review interval between refreshed training procedures for
control of work, materials and tools, paying particular attention to acceptance criteria</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Not qualified prior to operation. Poor quality control</td><td>x</td></tr>
<tr><td>Qualification degraded during operation. Poor preventive maintenance</td><td></td></tr>
<tr><td colspan="4">SAFETY CULTURE:
ROOT CAUSE: Why was it not prevented?</td><td colspan="2">How to prevent recurrence?
(Corrective actions by ASSET method)</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td colspan="2">Deficiency in timely eliminating the latent weakness:</td><td colspan="2" rowspan="3">Surveillance programme failed to detect the inadequacies of the procedure</td><td colspan="2" rowspan="3">III Engineering manager to review surveillance programme for administrative control procedures</td></tr>
<tr><td>Detection</td><td>x</td></tr>
<tr><td>Restoration</td><td></td></tr>
<tr><td colspan="2">Contributor to the existence of the deficiency

Inadequate policy for:</td><td colspan="2" rowspan="3">The policy guidance relating to the surveillance of administrative procedures was inadequate</td><td colspan="2" rowspan="3">IV Station manager to review the station policy for the surveillance of procedures</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Surveillance</td><td>x</td></tr>
<tr><td>Feedback</td><td></td></tr>
</table>

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG.III.3. Event root cause analysis form: reference plant 3, occurrence 2.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 3, OCCURRENCE 3		ASSET						
Event title:	Potential degradation of the safety function cooling the fuel due to damage to the motor of a reactor main coolant pump		Safety consequences due to initiating failure						
SAFETY PERFORMANCE: OCCURRENCE: What failed to perform as expected?			Corrective actions by plant						
Occurrence title:	Shift manager failed to assure that all administrative pre-start checks were completed before commencing plant warm-up								
Nature of the failure	x Personnel failure Equipment failure Procedure failure	x Occurrence results from a failure during operation Occurrence results from a deficiency discovered by periodic testing	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed		
SAFETY PROBLEMS: DIRECT CAUSE: Why did it happen?		**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No	
Latent weakness of the element that failed to perform as expected	Degraded safety awareness of shift manager in that he failed to assure that all administrative pre-start checks were completed	**I** Operations manager to review with the shift personnel the need for a constant questioning attitude and safety awareness and to ensure a high safety culture in the shift team							
Contributor to the existence of the latent weakness: Not qualified prior to operation. Poor quality control: Qualification degraded during operation. Poor preventive maintenance: x	Operation manager failed to detect deterioration of safety awareness of the shift manager	**II** Operation manager to discuss with shift manager and arrange training to enhance his safety awareness							
SAFETY CULTURE: ROOT CAUSE: Why was it not prevented?		**How to prevent recurrence?** **(Corrective actions by ASSET method)**							
Deficiency in timely eliminating the latent weakness: Detection: x Restoration:	Surveillance of the performance and safety awareness of personnel failed to detect latent weakness in the shift manager	**III** Human resources manager to review means of establishing effective surveillance of personnel effectiveness and safety awareness							
Contributor to the existence of the deficiency Inadequate policy for: Surveillance: x Feedback:	The application of the station policy relating to surveillance of personnel effectiveness and safety awareness was inadequate	**IV** Station management to review the station policy and its application across all disciplines							

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. III.4. Event root cause analysis form: reference plant 3, occurrence 3.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 3, OCCURRENCE 4			ASSET					
Event title:	Potential degradation of the safety function cooling the fuel due to damage to the motor of a reactor main coolant pump			Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title:	Control barrier attendant failed to detect that a tool was not brought out of working area								
Nature of the failure	x	Personnel failure	Occurrence results from a failure during operation: x	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
		Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected	Degraded safety awareness of barrier attendant in that he failed to follow the procedure to ensure that all equipment, materials, and tools were brought out after completion of work		**I** Operations and maintenance managers to (a) promote the need for a constant questioning attitude and high safety awareness among staff and (b) review administrative procedures and the controls for completion of work						
Contributor to the existence of the latent weakness:	Access control supervisor failed to detect deterioration of safety awareness of the barrier attendant		**II** Operations manager to discuss with access control supervisor the need to constantly observe and reinforce the safety awareness of his staff						
Not qualified prior to operation. Poor quality control									
Qualification degraded during operation. Poor preventive maintenance: x									
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:	Surveillance of the performance and safety awareness of personnel failed to detect latent weakness in the barrier attended		**III** Human resources manager to review means of establishing surveillance of the effectiveness and safety awareness of personnel						
Detection: x									
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:	The application of the station policy guidance relating to surveillance of personnel effectiveness and safety awareness was inadequate		**IV** Station manager to review the station policy and its application across all disciplines						
Surveillance: x									
Feedback									

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. III.5. Event root cause analysis form: reference plant 3, occurrence 4.

IAEA	EVENT ROOT CAUSE ANALYSIS FORM EXAMPLE: REFERENCE PLANT 3, OCCURRENCE 5				ASSET					
Event title:	Potential degradation of the safety function cooling the fuel due to damage of the motor of a reactor main coolant pump				Safety consequences due to initiating failure					
SAFETY PERFORMANCE: OCCURRENCE: What failed to perform as expected?					Corrective actions by plant					
Occurrence title:	MCP motor failed to trip on ground fault									
Nature of the failure		Personnel failure	Occurrence results from a failure during operation	x	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
	x	Equipment failure	Occurrence results from a deficiency discovered by periodic testing							
		Procedure failure								
SAFETY PROBLEMS: DIRECT CAUSE: Why did it happen?			**How to eliminate the problem? (Corrective actions by ASSET method)**		Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected		Electrical protection not designed to trip on ground fault	**I.** Revise protection scheme							
Contributor to the existence of the latent weakness:		Inadequate acceptance criteria in that the importance of potential for MCP motor fire due to persistent ground fault not recognized	**II** Review acceptance criteria and the methodology for determining the acceptance criteria							
Not qualified prior to operation. Poor quality control	x									
Qualification degraded during operation. Poor preventive maintenance										
SAFETY CULTURE: ROOT CAUSE: Why was it not prevented?			**How to prevent recurrence? (Corrective actions by ASSET method)**							
Deficiency in timely eliminating the latent weakness:		Surveillance of the safety case failed to detect the potential impact of the latent weakness	**III** Review procedures for surveillance of safety case							
Detection	x									
Restoration										
Contributor to the existence of the deficiency Inadequate policy for:			**IV**							
Surveillance	x									
Feedback										

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

FIG. III.6. Event root cause analysis form: reference plant 3, occurrence 5.

Annex IV

EVENT ROOT CAUSE ANALYSIS FORM (BLANK)

IAEA	**EVENT ROOT CAUSE ANALYSIS FORM**			**ASSET**					
Event title:				Safety consequences due to initiating failure					
SAFETY PERFORMANCE: **OCCURRENCE: What failed to perform as expected?**				Corrective actions by plant					
Occurrence title:									
Nature of the failure		Personnel failure	Occurrence results from a failure during operation	Ap-pro-pri-ate		Com-pre-hen-sive		Im-ple-ment-ed	
		Equipment failure	Occurrence results from a deficiency discovered by periodic testing						
		Procedure failure							
SAFETY PROBLEMS: **DIRECT CAUSE: Why did it happen?**			**How to eliminate the problem?** **(Corrective actions by ASSET method)**	Yes	No	Yes	No	Yes	No
Latent weakness of the element that failed to perform as expected			**I**						
Contributor to the existence of the latent weakness:			**II**						
Not qualified prior to operation. Poor quality control									
Qualification degraded during operation. Poor preventive maintenance									
SAFETY CULTURE: **ROOT CAUSE: Why was it not prevented?**			**How to prevent recurrence?** **(Corrective actions by ASSET method)**						
Deficiency in timely eliminating the latent weakness:			**III**						
Detection									
Restoration									
Contributor to the existence of the deficiency Inadequate policy for:			**IV**						
Surveillance									
Feedback									

NB: If more than one occurrence is selected from the event tree for root cause analysis, please attach as many forms as necessary.

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