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Determination of the root cause of the serious incident at Paks NPP on 10 April, 2003

KRISTÓF HORVÁTH,[a] JÓZSEF RÓNAKY,[b] JÓZSEF SOLYMOSI[c]

[a] *Head of Emergency Response & Training Section, Hungarian Atomic Energy Authority, Budapest, Hungary*
E-mail: horvath@haea.gov.hu
[b] *Hungarian Atomic Energy Authority, Budapest, Hungary*
[c] *Miklós Zrínyi National Defence University, Budapest, Hungary*

A serious incident occurred at the Paks Nuclear Power Plant (NPP) on April 10, 2003, in the revision shaft next to Unit 2 that was shut down for scheduled overhaul. 30 fuel-assemblies were damaged and, although negligible in its extent concerning the environmental impact, radioactive material was released into the environment. The event was classified as INES-3 on the 7-level International Nuclear Event Scale. In accordance with the international requirements, the event was independently investigated by the Hungarian Nuclear Safety Authority and analyzed by the methodology of Root Cause Analysis (RCA) in order to determine the primary cause of the incident. This report summarizes the different techniques of RCA and it introduces the steps of investigation from data and information collection through identification of relevant occurrences and causal factors to the development of effective corrective and preventive measures.

Root cause. *The cause that, if corrected, would prevent recurrence of this and similar occurrences. The root cause does not apply to this occurrence only, but has generic implications to a broad group of possible occurrences, and it is the most fundamental aspect of the cause that can logically be identified and corrected.*

Paks Nuclear Power Plant

The site of the Paks NPP is located in Tolna County, it is 115 km southward from the capital Budapest and 75 km northward from the southern border of Hungary. The site is located 3 km far southward from the town Paks, and 1 km westward from the river Danube.

The four VVER-440/V213 type, pressurized water reactors of the Paks NPP belong to the light water type: both the moderator and the coolant are light water (H_2O). The nominal electric output of each unit is about 460 MW.

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Address for correspondence:
KRISTÓF HORVÁTH
Head of Emergency Response & Training Section
Hungarian Atomic Energy Authority, Budapest, Hungary
E-mail: horvath@haea.gov.hu

Incident description

On 10 April 2003 while the assemblies were being cleaned during the course of the annual maintenance of Unit 2, severe fuel assembly damage occurred whereupon radioactivity was emitted that within the regulatory limits exceeded the value of the normal emission of a working unit.

Annual maintenance took place at Unit 2 on 10 April 2003 according to schedule. The cleaning of the fuel assemblies was carried out in Revision Shaft No. 1. The reactor internals were being cleaned at the same time. The cleaning of the fuel assemblies that was taking place in the cleaning vessel was completed at 16.55, while the cleaning of the inner elements of the reactor was still in progress. The temperature of the cleaning vessel was maintained at 37 °C by cooling, the cooling water was circulated by a submersible pump. At 21:53, radioactive Kr-85 gas was detected by the detectors mounted on the cleaning equipment and the reactor`s noble gas concentration meter indicated alarm level. Co-incidentally, the release monitoring systems mounted in the ventilation stacks indicated a sudden increase in noble gas emission. The engineer on duty suspended work in the reactor hall and ordered the evacuation of the area. An emergency maintenance working group was called together to evaluate the event and to determine what steps to take. They decided that the main tasks should be to open the lid of the cleaning vessel, to investigate the vessel visually, to analyze the water covering the vessel and – if possible – to identify which assembly/assemblies was/were leaking.

The hydraulically locked cleaning vessel lid was opened at 02:15 by FANP. Suddenly an increase in the activity concentration was detected by the radiation protection monitoring system and the water level in the spent fuel pond decreased by about 7 cm. The attempt to lift up the covering lid of the vessel failed since one of the three cables broke. After the successful lifting of the lid on 16 April 2003, severe damage of the assemblies could be observed by video camera investigation.

Event investigation

There are five steps in the event investigation process:

1. Collect and review information;
2. Assess the information; analyze the event/trend, determine causes;
3. Develop:
   - corrective actions locally to prevent recurrence of the event/trend;
   - preventive actions to eliminate precursors of future events;

4. Inform others of the lessons learned; this includes colleagues internal and external to the operating organization/country;
5. Conduct an effectiveness review of the implemented corrective actions.

An overview of some of the techniques available for use during the first and second steps of the investigation can be found below. Each technique is explained briefly, and additionally the results of the HAEA independent investigation are summarized.

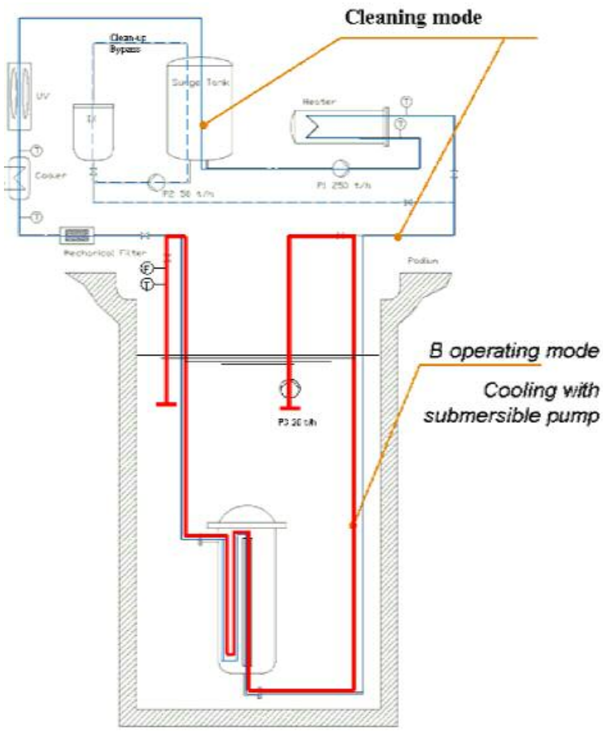

Figure 1. Technical scheme of cleaning equipment

Task analysis

Event Investigators are frequently expected to investigate events involving tasks with which they are not intimately familiar or where they may have little or no knowledge. In this instance it is advisable to find out more about the potential problems in performing a task by undertaking a task analysis. Hence investigators become 'instant experts' and are better prepared when it comes to talking to others about the task. A thorough task analysis can familiarize the investigator with details and potential problems associated with a task and enhance his/her credibility with interviewees.

There are two types of task analysis considered here. ‘Paper-and-pencil’ Task Analysis involves determining how a task should be done according to the written procedures and documents. It involves breaking a task down into small steps, usually by reference to a procedure, and identifying who performs each step, what the step entails, the component being worked on, and any tools required. It provides the investigator with an insight into a particular task and frequently identifies questions about the task that may be used later during information gathering by interviewing. Task analysis of this type is particularly useful for a root cause analyst who does not have specialized skills in the areas of work being investigated. It makes him/her familiar with a task, enables informed questioning during information-gathering and thereby enhances the investigator’s credibility.

The method was very helpful in determining contributory factors that relate to the physical environment where the task was performed. The facts collected and the questions developed were used as the basis of the interviews and site inspections made following the incident.

Another, in the object case not applicable type of task analysis is the ‘Walk-through’ Task Analysis. This is a step-by-step re-enactment of the task without actually performing any of the required actions. The purpose of this analysis is to determine how the task was actually performed. The walk-through should be performed with someone who normally performs the task as part of his normal job function. This could be the person(s) involved in the inappropriate action(s). The investigator observes and notes any differences between the actual performance re-enactment and the procedural steps. This technique can also be incorporated into an interview.

Change analysis

Change analysis looks at a problem by identifying the differences between what was expected and what actually happened. The basic questions are these:

a) “What has changed this time when something has gone wrong compared to all the previous occasions when nothing went wrong?”
b) “Could the change have been responsible for the consequence?”

Change analysis is the comparison of a successfully performed activity to the same activity performed unsuccessfully. During the process of collecting information, all identified changes or differences are written down. These are then examined to determine whether their effects resulted in an inappropriate action or undesired equipment condition.

Change analysis is a good technique to use when you don't know where to start or you suspect that some change has contributed to the problem. Whilst change analysis may lead to the root causes of simple problems it will not lead directly to root causes of more complex events; but nevertheless it can be effectively used to provide leads and to develop questions on which to follow-up with other techniques.

The use of this technique was evident during the HAEA's investigation since the cleaning process was performed successfully five times previously. The most relevant change found is the longer period of operation in B mode (intermediate cycle following the end of cleaning process, but before removal of fuel assemblies).

In the course of the investigation the basic questions of change analysis were:

a) What is different?
b) What is the effect of change?

The factors used during the analysis of the collected information were: what, when, where, how and who.

Barrier analysis

Barrier analysis is meant to provide answer to the following question: "What barriers should have been in place to prevent the undesirable outcome?"

Barriers are installed to promote consistent human performance that should inhibit inappropriate actions. Barriers can be administrative, in the form of procedures or other control documentation, or they can be physical restraints, in the form of locks or chains, etc. Barriers are designed and put in place to ensure consistent performance. Rarely in a power plant is one barrier relied upon, barriers are usually multiple and diverse, providing a 'defense-in-depth'. Human performance barriers in a power plant are predominantly administrative. Barrier analysis is conducted to determine why barriers failed and to identify missing or ineffective barriers. Barriers can also be used to mitigate the severity of an event by preventing adverse consequences from occurring after a human inappropriate action or equipment failure.

The following types of barriers were envisaged by the HAEA's experts.

a) *Create awareness* and understanding of the risks and hazards.
b) *Detect and warn* about the presence of off-normal conditions or imminent dangers.
c) *Protect* people and the environment from injury and damage.
d) *Recover* from off-normal conditions and restore the system to a safe state.
e) *Contain* the accidental release of harmful energy or substances.
f) Enable the potential victims to *escape* out-of-control hazards

The barriers identified either have worked, failed or been intermediate (no effect on incident). The sequence of the events and the action taken are summarized in Table 1.

Dates and times in the first two columns, actions in the third, conditions and behaviors in the fourth, identified causes in the fifth, while broken or missing barriers can be found in the last column.

The most relevant barriers identified as failed or missing are also visualized on Figure 2.

Event and causal factor charting

An event and causal factors chart (ECFC) provides a graphic display of the event on a time line. It relies on factual information entered in areas relating to ‘What’, ‘How’ and ‘Why’, and also shows the areas where barriers are ineffective or missing.

Event and causal factor chart is particularly useful for complex problem situations and are easier to understand than long narrative descriptions. It shows with special, standardized symbols the exact sequence of occurrences from start to finish and allow the addition of barriers, other conditions, secondary events, presumptions, and causal factors that influenced the event. Moreover, it provides a logical, factual and pictorial description of an event that directs the root cause analyst towards root causes.

The finalized events and causal factor chart with the most relevant actions can be seen on Figure 2. The events identified as inappropriate or undesirable are visualized with different symbol in the chart (see key to symbols on Figure 2).

Cause and effect analysis

This technique arrives at the underlying causes of an event in a very direct manner. The Cause and Effect process begins with a problem statement. This could be an inappropriate action/undesirable equipment condition, or simply the last ‘bad thing’ that happened. Cause and Effect then poses the question “Why?” and successively asks and answers this question, progressing backward in time. The end of the process should always be at a cause/answer that is directly influenceable, i.e., correctable within the operating organization.

The most relevant identified causes are visualized in the Summary Event and Causal Factor Chart (see Figure 2), while the entirety of the causes can be found in Table 1.

The HAEA’s experts divided the unconformancies (causes) found into groups:

a) legal unconformancies
   - deviations from the prescription of the Nuclear Safety Code (No. 3)
   - deficiencies of the Nuclear Safety Codes
b) technical, professional unconformancies
   - during design, preparatory phase
   - during operation and the management of the incident
c) quality unconformancies

Interviewing

Interviewing is the single most important and direct method of data gathering. It is a reliable way to establish the facts and to determine behavioral factors and causal factors. However, it must be emphasized that interviewing should be *fact*-finding not *fault*-finding.

Interviewing involves the preparation of questions – many derived from other techniques such as task analysis and change analysis, followed by face-to-face communication with those involved in the event. In order to get to the root causes of events it is imperative that those being interviewed are made to feel that they are contributing to an improvement process by helping to find weaknesses in local systems so that others may avoid the same problems: they must not feel that they are on trial. It helps the investigator enormously if the interview can be undertaken in a blame-tolerant situation.

Interviewing does have limitations: it can be very time-consuming and requires a fair degree of skill on the part of the investigator. Facts become less clear as the time between the event and the interview increases, consequently, the interviewee may not recall all of the details.

Three teams of HAEA's regulators performed the site inspections. The questions developed and the details requiring further investigation were divided into three groups, thus each group focused on one topic. The topics and objectives of the investigations made by different teams, and the interviewees are described in Table 2.

Table 2. Topics, objectives and interviewees

Team	Topics and objectives	Interviewees
No. 1	Event sequence till the first attempt to lift the head of the vessel – Getting to know the actual status of the equipment – Controlling the design information – Parameters, conditions leading to the event	– Representative of FRAMATOME ANP (who operated the device at the site) – Chemist (assisting the vendor) – Technical coordinator
No. 2	Sequence and management of events from the first attempt for lifting the head of the vessel – Becoming acquainted with the scenario of the event	– Duty engineer – Unit supervisor – Representative of FRAMATOME ANP (who operated the device) – Responsible program-leader – Dosimetry shift leader
No. 3	Decision processes, management of the incident – What kind of decisions were born, whether they were reasonable and planned? – Who were authorized to take decision? – Tracing the information flow – Relation between the actual conditions and the main outage activities	– The chairman of the Maintenance Working Committee (on 9th of April) – Duty engineers and unit supervisors from 10 pm on 10th of April

Assessment of human performance

Information processing apparently operates in one or more of three modes: skill-based, rule-based, and knowledge-based. Referred to as performance modes, they are based on the level of familiarity an individual has with a specific task and the level of attention (degree of information processing) a person applies to the activity. The performance mode of the personnel, who performed the activities before and during the incident occurred on 10th of April was identified as rule based performance.

Error modes

Problems discovered during a task usually require a different skill than planned to accomplish the task successfully. The active error modes identified were as follows:

a) Execution errors – correct understanding of situation and correct intentions involving inadvertent slips and unintentional omissions; not recognizing changes in task requirements, system response, or plant conditions associated with task due to some preoccupation. Or, so strong intent on task that pertinent information is not detected, i.e., overattentive.

b) Interpretation errors – not fully understanding or detecting conditions calling for a particular response; responding to a deviation from plan; applying the wrong procedure to the situation or applying the correct procedure for the inaccurately perceived situation.

c) Diagnosis errors – flaws in problem-solving and decision-making based upon erroneous mental representation of the system/plant status; typically based upon insufficient information about the true plant or equipment status.

Anatomy of an event

Figure 3 shows the anatomy of an undesirable consequence (event) to the facility generally in terms of reduced safety margin. The initiating action is an action by an individual that results in a plant event. The error precursors are undesirable prior conditions that reduce the opportunity for successful behavior at the jobsite. Flawed defenses are defects with defensive measures that, under the right circumstances, may fail to protect plant equipment or people against hazards or fail to prevent the occurrence of active errors. The latent organizational weaknesses are undetected deficiencies in the management control processes (e.g., strategy, policies, work control, training, and resource allocation) or values (shared beliefs, attitudes, norms, and assumptions) creating workplace conditions that either provoke error (precursors) or degrade the integrity of barriers (flawed defenses).

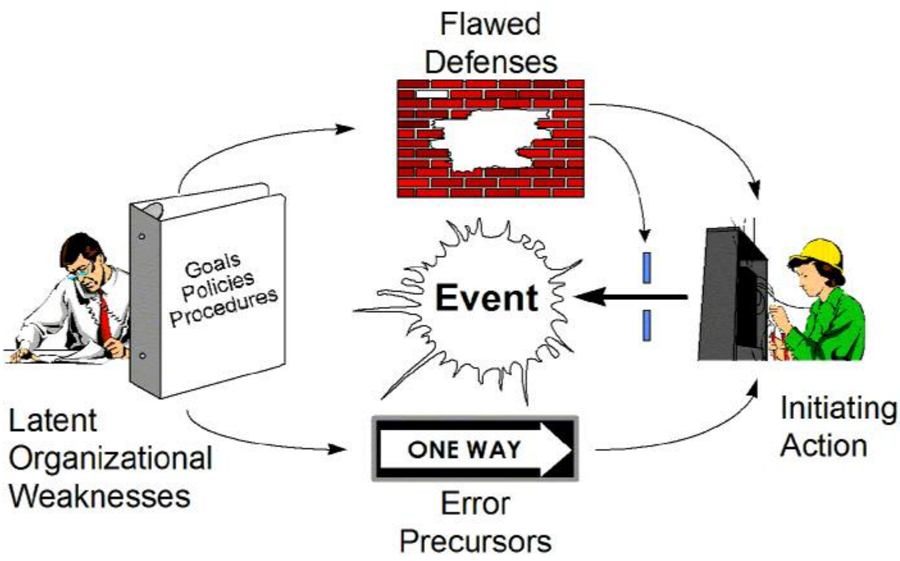

Figure 3. Anatomy of an event

Task characteristics and error precursors

Tasks can be described using attributes common to any work activity. Conditions, positive or negative, associated with these attributes can be used to describe a specific task situation. Task-specific conditions can be grouped into one or more of the following attributes:

a) Task demands are specific mental, physical, and team requirements necessary to accomplish a particular task successfully, e.g., workload, time pressure, roles and responsibilities, and standards.
b) Individual capabilities are unique mental, physical, and emotional abilities of a particular person assigned a specific task, e.g., familiarity with task, values, education, knowledge, skills, attitudes, personality, experience, health and fitness, age, communication practices, and self-esteem.
c) Work environment means general influences of the workplace, organizational, and cultural conditions that affect individual behavior, e.g., distractions, equipment layout, tagout procedures, shared norms and values, attitude toward various hazards, and work control processes.

d) Human nature covers generic traits or dispositions of being human; human limitations that may incline individuals to err under certain unfavorable conditions, e.g., habit, short-term memory, fatigue, stress, complacency, emotion, and mental shortcuts.

Unfavorable conditions that create mismatches are known as error precursors. As outcomes of latent organizational weaknesses, error precursors produce mismatches at the jobsite that reduce the chances for success, or increase the probability for error.

The HAEA's experts made detailed analysis and evaluation of the actions of the operating personnel. The statements of the investigation were linked into the following groups:

a) Period prior to the operation of the cleaning technique
b) Deposition team
c) Deficiencies during the preparation of the cleaning technique
d) General evaluation of the organization of the NPP
e) Activities of the personnel during the management of the incident
f) Decision making
g) The activity of the personnel responsible for operation
h) Other contributing personal and leadership processes

Development of corrective/preventive actions

The output of any event investigation, irrespective of the root cause analysis methodology used, is of little value if it merely identifies root causes, error-likely conditions and flawed defenses/weak barriers. The step that will prevent the next event is the development and implementation of effective corrective and preventive actions. Effective actions will improve management systems and safety culture within the operating organization. Presuming that prompt action has been taken to mitigate the effects of the direct /immediate cause, using an Event & Causal Factors Chart (or similar) together with other selected root cause analysis techniques will facilitate easy development of effective corrective actions that address the root causes, error-likely conditions and broken or ineffective barriers.

Corrective actions should have the following attributes: be specific and practical; have content and timescale agreed by the recipient of the action, i.e., persons accountable and responsible for the actions; be prioritized.

In developing and implementing corrective actions, consideration of the following questions can help to ensure that the actions will prove to be effective:

a) Do the corrective actions address all the root causes?
b) Will the corrective actions cause any detrimental effects?

c) What are the consequences of implementing the corrective actions?
d) What are the consequences of not implementing the corrective actions?
e) Will training be required as part of the implementation?
f) In what time frame can the corrective actions reasonably be implemented?
g) What resources are required for successful development of the corrective actions?
h) What resources are required for the successful implementation and continued effectiveness of the corrective actions?
i) What impact will the development and implementation of the corrective actions have on other work groups?
j) Is the implementation of the corrective actions measurable?
k) Are the closure criteria clear, such that it will be readily apparent when the corrective actions have been satisfactorily completed?

In short, corrective actions should be S M A R T, i.e., Specific, Measurable, Achievable, Realistic, Timely.

The below list describes the hierarchy of effectiveness of the preventive actions:

a) design or design change to eliminate or reduce the hazard
b) install automatic safety devices
c) install automatic safety warnings or alarms
d) procedures or procedure changing
e) personnel (training, knowledge, etc.)
f) identify and accept assumed risk.

The urgent corrective and preventive measures decided and declared by the HAEA's regulators were grouped as follows:

a) Regarding legal deficiencies
b) Regarding design deficiencies
c) Regarding the internal regulatory system of the Paks NPP
d) Regarding leading activity and decision making processes of the Paks NPP
e) Regarding organizational issues
f) Regarding safety improvement measures
g) Regarding the safety culture.

Conclusion

Among the various efforts to improve operational safety of facilities, the systematic collection and evaluation of operational experience are considered valuable and effective. This may be achieved by establishing a system for the effective feedback of operational experience. Such a system enables all safety related occurrences to be analyzed, root causes determined and corrective and preventive actions implemented to avoid recurring events or events rooted in the same causes.

This publication outlines some of the simple tools that enable event investigators to discover the causes of events or adverse trends and to develop the corrective and preventive actions that are most likely to obviate recurrence of the event or adverse trend. These tools should be used by the investigators during the assessment of an event such a way as a football player applies the different techniques (sliding tackle, sprinting, passing, kicking etc.), choosing the most effective one depending on the situation. Application of these techniques is 'tried and tested' in a wide variety of industries and their effectiveness has been especially well-proven in the nuclear industry worldwide.

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