Lessons Learned from the INES-3 event at PAKS NPP on April 10, 2003

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ABSTRACT: A severe incident occurred in the Paks NPP on April 10, 2003: thirty fuel assemblies remained without sufficient cooling for longer time in the equipment designed for chemical cleaning of the spent fuel and therefore they suffered severe damage. Several investigations were conducted to analyse the scenario of the incident and to identify its causes. The event was evaluated on the one hand by the operator and on the other hand by the Hungarian nuclear authority. In addition it was done also by the designer and the manufacturer of the equipment – the FRAMATOME ANP - and by the German GRS. At the request of the Hungarian Government also a team of the IAEA consisting of 10 experts, based on the performed analysis and on-site investigations, prepared a report about the incident. There are differences in the identification of the root causes depending on how long they went back into the preceding events. Relevant lessons can be learned by every participant from the mistakes made during the design, manufacturing, regulatory licensing and inspection, operation and during the incident itself, while further issues need to be solved in order to eliminate the consequences of the event. The specialty of the event is that it occurred apart from the energy generating technology, on an independent system established for special purpose, and the severe fuel damage was induced by the coincidence of various errors that were mostly independent from each other. The event was classified according to the IAEA event scale as INES-3 i.e. as severe incident.

1 INTRODUCTION, BACKGROUND, PRECEDENTS

Four VVER-440/213 type Soviet designed reactor units are in operation in the Paks Nuclear Power Plant (Paks NPP). The dates of commissioning are in sequence: 1982, 1983, 1985 and 1986. The operational records of the power plant were outstanding and in the meantime it performed continuous development both for increasing the efficiency and for improving the safety. Among the latter the safety upgrading program, which was carried out between 1996 and 2002 with the expenditure of around 250 Million USD has to be emphasised. With this development, the design safety of the power plant – based on the unanimous opinion of international experts – reached the safety level of the Western reactors of the same vintage. However problems also emerged during the operation. Among them the most significant is that series of events, which resulted magnetite deposits in the fuel assemblies and finally caused the severe incident on April 10. 2003.

In the case of the VVER type reactors, already in the early 90s', it was observed that some of the jet nozzles of the carbon-steel feedwater-collectors inside the steam generators (SGs) fell down and as a consequence the necessity of the replacement of the collectors could be foreseen. This work requires welding and assembling activities inside the upper part of the steam generators. The replacement of the collectors of 6 SGs per unit (in case of the Paks NPP altogether 24) would have resulted significant collective dose of the workers, therefore protection was necessary to apply. At most of the NPPs it was solved by shielding, while at the Paks NPP the decontamination of the SGs was decided. The decontamination for the first time was applied in 1995-96 at the Unit 2, then all SGs of the Units 1-3. were decontaminated in 2000 and 2001. It was a serious mistake.

The deposition of the corrosion products (cruds) on the surface of the SG tubes is inevitable, normal phenomenon. The removal of them is ensured by the designed filtering systems and a certain material quantity is removed also with the assemblies during the periodical refueling. The extended number of simultaneous decontamination processes resulted imbalance and the extra corrosion product (magnetite) deposited on the surface of the fuel elements and formed significantly thicker layer in comparison with the normal one (80 vs. 10-20 μm). Due to rapid temperature changes during automatic operation of the reactor protection system, the deposits delaminated from the surface of the fuel elements and spilled to the bottom of the vessel, however the majority stuck on the lower spacer grid. This phenomenon led to core asymmetry, which was the consequence of the non-uniform distribution of the cooling water flow rate. Due to the limiting effect of the outlet coolant temperature the power of the units had to be decreased, which caused economical losses. At the same time the authority obliged the licensee to examine what safety limits concerned the core burdened with crud, as the available analysis related to clean fuel elements.

In 2000 the management of the nuclear power plant decided to solve the problem definitively. In the case of replacement of the feedwater-collector of unit No.4, the decontamination was not permitted, but the dose-rate was decreased by shielding (application of lead coverings and of increasing the SG water level). At the same time Paks NPP entrusted the FRAMATOME ANP (FANP) to perform the cleaning of the fuel elements burdened with cruds. For this purpose the AMDA technology was to be used, which was already successfully applied in 2000-2001, but instead of the tank applicable to 7 fuel assemblies it should be equipped with a tank that can receive 30 assemblies in one single batch.

Signing the contract between the Paks NPP and the FANP took place in November 2002. The first batch, containing 30 fuel assemblies were loaded into the tank in March 2003. Since this was the first time to apply such facility for cleaning fuel assemblies, during the available four months the designing, manufacturing, assembling and installation of the equipment had to be performed, while the licensing processes had to be conducted as well. It is not doubtful that such a pressed time schedule could result in making significant mistakes.

In the license application submitted to the regulatory authority the equipment was classified into safety class 3, which was approved by the regulator. This classification then specified the licensing process. In such a case, according to the Nuclear Safety Regulations, the nuclear safety authority issues only license in principle, and the further actions do not require regulatory license. They can be performed within the authority of the licensee in accordance with its internal procedures. It was also proved to be a mistake as turned out later on.

2 THE EVENT ITSELF

The detailed scenario of the event could be read in several sources ([1], [2], [3]), therefore it will here be reported only those momentums, which are – in my opinion – of basic importance to draw the conclusions, as follows:

Date and time	**Occurrence**
April 10, 2003	
16:00	The cleaning of the 6th batch (30 assemblies, just taken out of the reactor) was finished. However, the assemblies were not removed from the cleaning tank, because the crane required for the lifting of the lid of the tank was busy for cleaning the internal structures of the reactor of unit No.2.
16:40	The AMDA was switched to «B» operating mode. Cooling of the fuel assemblies was ensured with the submersible pump circulating water being inside the service shaft.
21:50	The counts on the Kr-85 measuring device of the AMDA system suddenly increased.
21:53	The warning limit was reached on the noble gas detector placed on the reactor platform of the unit No.2, the measured value was 1700 kBq/m^3.
22:50	The head of the Dosimetry Service evacuated the reactor hall.
23:45	The measured value on the noble gas detector placed on the reactor platform was 26100 kBq/m^3. Following the instructions of the Shift Supervisor the maintenance ventilation systems of the reactor hall were started, hence the ventilation of the reactor hall operated with full capacity.
April 11, 2003	
02:15	The hydraulic locks, which ensure the leak tight closing the lid of the cleaning tank were loosened by the technician of the FANP. Simultaneously with the loosing of the lid of the cleaning tank the gamma dose rate significantly increased in the vicinity of the spent fuel pool and the service shaft (6-12 mSv/h).
12:40	The Safety Director ordered the partial alerting of the Emergency Preparedness Organisation (telecommunication and radiation assessment groups).
13:15	The Shift Supervisor initiated measures in order to decrease the release to the environment.
April 16, 2003	
16:23	The lid of the cleaning tank was lifted. No increase was observed on the radiation measuring (SEJVAL) system.
20:00	It was found during the visual observation, (using remote control camera), that the fuel elements inside the tank were significantly damaged.
22:30	The Paks NPP declared stage "ALERT" and alerted its Emergency Preparedness Organisation.
April 19, 2003	
10:00	The boric acid concentration in the spent fuel pool was increased to the value of 16 g/kg in order to ensure the appropriate sub-criticality. The reliability of the cooling system of the cleaning tank was ensured by the newly installed pump provided so higher redundancy. One of the pumps was sufficient for cooling while the other one served as reserve.
April 20, 2003	
09:00	The Safety Director terminated the operation of the Emergency Preparedness Organisation.

3 INVESTIGATION

3.1 Event investigations

In accordance with the regulations, the licensee shall report every single event to the authority. The Shift Supervisor reported the event to the Inspector on Duty of the HAEA NSD via phone at 00:30 on April 11, 2003. The licensee shall perform a detailed investigation within 30 days for the regulatory authority about the scenario of the event, the identification of the causes and the measures necessary to prevent the recurrence of similar events. The regulator reviews and evaluates the report and sends its opinion – agreement or request for additional measures – via mail to the licensee.

Concerning the severity of the incident occurred on April 10, 2003, the regulatory authority has decided to conduct an independent investigation. For this reason it established an expert team, which launched an investigation based on its own database, several times visited the site, made interviews with the employees of the Paks NPP and the FANP, collected documents and video-records, and gathered additional information via video-conferences.

The event investigation report of the Paks NPP was submitted to the HAEA NSD on May 10, 2003. The root cause of the event was determined as insufficient cooling.

The detailed report of the HAEA NSD was issued on May 23, 2003. In this report the HAEA NSD analyzed in every particular details the precedents of the incident. It described the steps made to manage and mitigate the deposits, its attention drawing through mentioning and identification of the deficiencies observed in the field of safety management and nuclear safety, and in addition the scenario and evaluation of the event. The weaknesses of the cleaning tank design were identified as primary root cause of the incident. Non-compliances were also presented in the report of the NSD concerning legal, technical and quality management fields. The report evaluated also the statements of the investigation report of the Paks NPP and judged them as not properly self-critical and not adequately comprehensive, therefore it required supplementation. The NSD did not analyse its own activity, this chapter was elaborated by a three-member committee nominated by the Director General of the HAEA and was independent from the NSD. According to their statements the actual regulations do not give proper instructions to the depth and details of the regulatory assessments, therefore their correction is necessary.

An independent IAEA mission asked for by the Hungarian government performed its review between June 16-22, 2003 in Hungary. Ten experts from six countries and from the IAEA reviewed the activity either of the licensee, the regulator and the sub-contractor. The review mission relied basically on the above mentioned two reports, but the experts completed their knowledge by on-site interviews and by studying the relevant documents.

The draft of the IAEA report was handed over to the Hungarian counterparts for comment at the end of mission. The Hungarian remarks were submitted on June 30, 2003, and the final report of the IAEA was received by the HAEA and the Paks NPP on August 10, 2003.

The IAEA report identified the extended number of decontamination of the steam generators as the root cause of the event. Altogether 45 suggestions were formulated, among them 16 concerned the Paks NPP, 14 concerned the HAEA, 9 concerned both of them and 6 concerned other authorities. The most relevant critical statements of the report were as follows:

- no conservative approach was applied in the assessment,
- the contractor worked without proper supervision of Paks personnel,
- HAEA underestimated the safety significance of the cleaning facility,

- the aggressive schedule of the process was a significant contributor to decisions of all players,
- eight different design deficiencies have been identified.

3.2 Analysis for clarification of the scenario

Following the incident, numerous Hungarian institutions – research institutes, university institutes, but also Paks NPP and the nuclear safety authority themselves and the designer-manufacturer FANP as well as the German GRS – have analysed and have been continuously analysing the scenario of the event in order to reconstruct and quantify the occurrences.

The analysis focus on three areas:

- subcriticality,
- thermohydraulic processes,
- fuel element behaviour.

Based on the analysis performed so far, it can be stated that:

- it cannot be excluded yet but is more than probable that the fuel elements did not reach the criticality either during or following the incident,
- during the heat-up phase (decreasing flow-rate, increasing temperature) the coolant reached the saturation temperature after around 6000 seconds,
- the upper dome of the tank became filled up with steam in around 8000 seconds, and after additional 1000 seconds the water level decreased to the one third of the height of the tank,
- after 8000 seconds the temperature of the cladding increased rapidly, the pressure of the gap also increased that led to the plastic deformation and ballooning, then cracking of the cladding,
- during the high-temperature phase (around 800-1200 °C) the temperature stabilised, there was no sign of melting, but hydrogen generation (originating from Zr-steam reaction) undoubtedly occurred (based on estimations the total quantity of H_2 was around 3 kg)
- fuel assembly shroud oxidation was almost complete in the upper part,
- during the quenching phase severe fuel damages occurred mainly by mechanical effect of water hammer entailing high releases of activity; intensive steam production could increase further the pressure inside the assemblies.

The APROS (HAEA, TUB INT), the ATHLET and the FRAP-T6 (KFKFI-AEKI), the ASTEC V1 (VEIKI Co.) and the GFX 3D (TUB INT) codes were applied for thermohydraulic and fuel behaviour calculations. Significant differences were found in the estimated cladding temperatures. This can be explained with the lack of precise knowledge of conditions being inside the tank during the incident. On the other hand the computer codes used for the analysis have not been validated to these conditions.

4 LESSONS LEARNED FROM THE EVENT

There are many lessons learned from the event. These are not applicable only for the operator and the regulator as the main players of the story but also for the subcontractors and the technical support institutes of both organisations. In my paper however I deal only with those lessons, which have been learned until now by the Paks NPP and the HAEA-NSD.

General conclusions can be drawn for all operators according to my personal judgement as follows:

- decontamination beyond a certain extent can cause a source of corrosion products and can lead to serious deposits even in the reactor core
- decision to apply any temporary facility for spent fuel treatment needs increased preparatory work and due foresight
- from too much trust in any subcontractor should be refrained also in the case of its high reputation
- aggressive scheduling of any activity has to be avoided, urgency increases the probability of failures originated by human actions especially in decision making processes
- perfect understanding of design and operational features of the actual system is necessary requirement imposed to the operation personnel
- the licensee has the full responsibility for safe operation of any equipment installed inside the plant, the responsibility cannot be designated to or shared with anybody else
- questioning attitude as well as conservative approaches are especially important in the case of an equipment or facility, which are outside the everyday O&M activities.

After the regulatory review of the event NSD requested the licensee to define tasks to be implemented to avoid recurrence of such event. Responding this request Paks NPP sent a list of improving measures decided to introduce until the end of this year. Some measures have been extended to longer term to be implemented because of their nature. In their list they took into consideration the statements, findings and recommendations made by the NSD in its event review report.

Without reporting the complete list, which consists of 24 items altogether, the most important ones are as follows:

- self-assessment will be carried out to identify weaknesses of the organisational structure and safety culture
- review of the internal regulations and procedures have been decided aiming at especially to reduce to the minimum the amount of special and unique prescriptions
- review and revision of procedures serving for inspecting the complete activity of subcontractors and especially the assessment, verification and approval of design documentation are necessary
- development and application of emergency operation procedures for equipment and systems installed temporary are inevitable
- development and introduction using quantitative symptoms of different rates of damaged fuel elements have been decided
- it has to be achieved that responsibility of individuals in the decision making process be unambiguously defined
- Safety Department of Paks NPP must be strengthen to be capable making independent evaluation of regulatory submittals in every technical area
- every available means have to be applied to avoid time pressure originated by tight scheduling for licensing process.

Lessons learned from the event also for the regulatory body were identified as follows:

- safety significance of modification licensing process has to be relied on the safety categorisation and safety classes taking into account the potential risk of the modification
- HAEA-NSD has to improve its safety review and assessment procedures to give more detailed guidance for the reviewer
- licensing process of an out-of-technology facility needs special care from all contributors because of its unique nature. It is not a good approach to look for analogies written in the regulations and

guidelines and applied them mechanistically. Both the main system and operational mode as well as all auxiliary equipment and modes have to be treated with the same care

- according to the Hungarian legal basis nearly every change of safety related structure, system and component requires license from the HAEA. It imposes heavy burden to the limited number of staff available for this task. Urgent amendment of legal documents has to be initiated to reduce number of licenses concentrating only to the most safety significant modifications
- HAEA has developed a program for introduction of risk-informed decision making into its licensing activity. It has to be accelerated
- safety performance indicator system based on the IAEA recommendations have been introduced in the HAEA in 2001. Using the indicators and other early signs certain deterioration in the safety culture level has been recognised and reported in different documents however there was no enforcement action applied. It is very difficult to make a judgement on the necessary regulatory intervention in this field.

5 PRESENT SITUATION AND OUTLOOK

More than half a year after the severe incident there are two most important tasks to be performed: recovery of the cleaning tank containing the damaged fuel assemblies and to restart unit No.2 as soon as possible but without making any compromise to the safety.

In the tank and in its surrounding the situation is stable. Neutron detectors and equipment for monitoring technological and radiation parameters have been installed and an autonomous cooling system of the service shaft is under construction. Boron injection facility is available for the case if boron concentration would decrease from any reason. Several times inspections of the internal part of the tank were carried out using special underwater video camera, which made it possible to get a clear picture on the geometry and composition of the fuel rods, assembly shrouds and debris located above the bottom plate. This information is very important for development of the recovery action plan.

Tendering process was issued by Paks NPP for recovering action. Two bids arrived, one from the FRAMATOM ANP the other from a Russian consortium lead by TVEL, which is also the producer of the fresh fuel assemblies for VVER rectors. After evaluation of the bids decision was made in favour of TVEL and the contract were concluded recently. The work includes a six months preparatory and a two months implementation phase, altogether 8 months. This period of time does not include the licensing activities. The sum of the contract is 4.55 USD.
Removal of the debris will be made using mostly manually remote control equipment with different catchers and tweezers. The pieces taken out will be placed to special small containers located around the cleaning tank and after covering they will be transported to the spent fuel pond for interim storage.

Concerning restarting the unit No.2 significant effort is being made by Paks NPP to develop the technology for how it would be possible to operate the unit No.2 without availability of the service shaft and parallel doing the recovery work in the reactor hall. The HAEA and other authorities are working on criteria for nuclear safety and radiation as well as transport safety of this complicated manoeuvre. It is still too early to predict the outcome of this effort.

There is an interesting aspect of this incident having produced a valuable experimental object interested in many countries to use it for better clarification of fuel behaviour after a deficiently cooled and significantly up-heated condition. Initial meeting was held in August of 2003 in Budapest with participation of representatives of the IAEA, OECD-NEA, US NRC, GRS (Germany) and IRSN (France), the Russian consortium and the Hungarian partners (HAEA, KFKI-AEKI, VEIKI Co., Paks NPP). The CSNI of OECD-NEA, together with the IAEA expressed their willingness to co-ordinate and sponsored an international research project in this subject. Hot cell examinations have been proposed to perform measurements for clarification conditions and properties of the parts of damaged fuel assembly. Additionally to the experimental work also analysis using thermal-hydraulic and fuel codes are planned to carry out. Financial support or/and in-kind contributions are expected from countries operating such type of reactors as well as from countries with large nuclear programmes. The project is planned to start in the first half of 2004.

REFERENCES

1. Event Investigation Report, No.1120.; Paks Nuclear Power Plant, May 10, 2003.

2. Report to the Chairman of the Hungarian Atomic Energy Commission on the Authority's Investigation of the Incident at Paks NPP on 10 April 2003; Hungarian Atomic Energy Authority, May 23, 2003.

3. REPORT of the EXPERT MISSION "To Assess the Results of the Hungarian Atomic Energy Authority Investigation of the 10 April 2003 Fuel Cleaning Incident at Paks NPP"; IAEA-TCR-01769, 2003.

ABBREVIATIONS

GRS	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
HAEA	Hungarian Atomic Energy Authority,
HAEA NSD	HAEA Nuclear Safety Directorate
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale
IRSN	L'institut de Radioprotectionet de Surete Nucleaire (France)
KFKI AEKI	KFKI Atomic Energy Research Institute, Hungary
OECD NEA	OECD Nuclear Energy Agency
Paks NPP	Paks Nuclear Power Plant, Hungary
US NRC	US Nuclear Regolatory Commission
TUB INT	Technical University Budapest, Institute of Nuclear Techniques
VEIKI Co.	Institute for Electric Power Research Co. , Hungary