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FIRE PROBABILISTIC SAFETY ASSESSMENT FOR KUDANKULAM NPP IN INDIA

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ABSTRACT

Fire Probabilistic Safety Assessment (PSA) was carried out by Atomenergoproekt, Moscow for Kudankulam NPP in design. The PSA addressed fire events initiated during plant operation at full power. Fire hazard analysis was an essential part of the fire PSA that resulted in design changes. Estimation of the fire frequency for all critical plant locations and identification of the resulting fire-induced initiating events and dependent failures were performed. The overall result of 9.1E-9 per reactor year represents approximately 17% of the frequency core damage caused by internal events. The methodology used in the study, results and findings found are described.

INTRODUCTION

A fire Probabilistic Safety Assessment (PSA) is a useful tool for supplementing deterministic analyses on which the Kudankulam plant design and fire protection are based. The first phase of the fire PSA was performed at the Preliminary Safety Analysis Report (PSAR) stage according to contractual terms. Since that time Russian fire protection standards have been raised. In 2004 the Russian Regulatory Authority published the document [1] that requires a fire PSA to be carried out at the PSAR stage. Thus, now this is regulatory requirement.

PLANT DESIGN FEATURES

Design features ensured that the necessary safety functions could be maintained during and after a fire. These included substantial physical separation of cables and systems providing redundant safety functions, a high degree of fire resistance of structural elements of safety and normal operation systems, implementation of weakly combustible cable insulation, and use of fire resistant control circuits at control rooms, where redundant equipment and cables of systems required to achieve and maintain stable shutdown conditions are located in proximity to each other. The established criteria specify fire barriers between redundant trains to have a minimum fire resistive rating of 3 hours. Each of four safety trains has the capability to provide heat removal from the reactor and maintain control and monitoring activities should a fire occur in another train.

The most important feature of the Kudankulam design is associated with the fact that safety systems comprise new passive technologies. For instance, emergency residual heat removal is fulfilled by two diversified redundant systems, one of which is operated in passive mode. From a fire protection point of view a passive heat removal system (PHRS) is of ultimate importance. This system consisting of four independent circuits of natural secondary coolant circulation is intended for long-term residual heat removal from the reactor both with sealed and leaked primary circuit in the case of loss of all auxiliary power supply sources (including emergency ones). The PHRS is designed in such a way that it is able to operate in all NPP operation modes, both independently and in combination with other normal operation and safety systems.

METHODOLOGY

The methodology applied is based on the IAEA Guidelines [2,3] and Russian experience in similar activities [4-8] being carried out since the mid-1990s.

The general approach for conducting a fire PSA was little changed from that used in the studies for operating plants. Preparation of the necessary data for the fire PSA project was very difficult due to incomplete information and documentation, e.g. lack of operating procedures. Some typical tasks were impossible to perform, e.g. plant walkdowns. Therefore the methodology typically used for performing a fire PSA of operating plants needed to be revised.

On the one hand the uncertainty associated with the results of the fire PSA are relatively high, on the other hand the fire PSA was recognized as a valuable tool that can provide insights into plant design. Carrying out the fire PSA from the very beginning of the design development gave the benefit of modifying plant design easily to mitigate fire consequences. Therefore, a through fire analysis could provide an extremely cost-effective approach to fire protection improvement at the design stage. Such a benefit is impossible when performing a fire PSA for operating plants.

The study was performed in a highly iterative manner, i.e. certain tasks needed refinement after conducting one or more of the subsequent tasks or incorporating changes to the plant design.

The fire PSA involved building and room analyses (including fire hazards analysis), screening technique, determination of fire-induced events and systems with reduced functionalities due to a fire, definition of fire related event sequences, quantification of the core damage frequency (CDF), uncertainty, sensitivity and importance analyses.

It should be noted that a more comprehensive PSA for internal fires will be performed during the detailed design, providing extensive documentation for the plant operating staff for their fire protection program.

FIRE HAZARDS ASSESSMENT

Fire hazard analysis was a comprehensive assessment of potential fire hazards throughout the plant and the effect of potential fires on the safety-related plant areas. This was an essential fundamental part of the fire PSA. It included determination of fire compartments, identification of potential fire hazards, determination of impacts of a fire in a compartment, and identification of fire induced initiating events. A fire containment approach was accepted as the design basis, which assumes that all combustibles within a fire compartment can be consumed during a fire without a failure of compartment boundaries regardless of operation of fire suppression systems.

The plant was divided into the fire compartments for purpose of evaluation of fire consequences, which coincide with structural components and fire resistance barriers. Judgment and experience were used to determine the adequacy of the fire protection measures for each compartment, and the possibility of propagation to other compartments. All the boundaries of a fire compartment credited as fire barriers (wall, floor, ceiling, doors, ventilation dampers, and penetrations) were evaluated carefully. A fire was supposed to propagate via a fire barrier if the duration of the standard fire would be longer than the fire resistance of the barrier expressed in hours.

In the case of high cable concentrations additional protection for the area of concern was provided, i.e. the deterministic analysis resulted in widespread physical changes to the plant such as additional fire barriers.

Examples of the plant modifications incorporated in the design are: (a) constructing fire barrier walls between redundant cables to divide the containment annulus into smaller compartments; (b) providing cooling for those compartments; (c) replacing surplus fire doors by fire-rated walls in cable shafts; (d) reinforcing fire-rated doors in some compartments of the auxiliary reactor building; and (e) enclosing cables in conduit to prevent cables from contacting other equipment in the fire compartment. In the last case the fire resistance rating of the fire-retardant wrap was designed to be equivalent to that of the fire compartment barrier walls.

The fire PSA followed a two-phase approach. In phase 1, a screening analysis was performed to identify the critical or important fire locations and screen out those areas that are not risk significant. In phase 2, a detailed analysis was performed for the important fire scenarios. Fire areas which have either safety-related equipment or associated cables were identified as requiring further analysis. The process, electrical and cable compartments were included into the analysis. The compartments not containing vital equipment were screened from consideration.

Much efforts were made in the deterministic fire hazard analysis to establish the failure modes of equipment and especially electrical circuits as a result of a cable failure. The circuit analysis was performed to identify the power, control, and instrumentation cables that are necessary to support the operational requirements for active safety-related equipment that is electrically controlled and/or powered. The types of cable failures considered are: short circuit, short to ground, open circuit, and hot short. A fault of the last type can lead to actuation of non-energized circuits. The lack of detailed design information on cable routing was resolved by means of addressing the worst case situation.

Fire consequences were defined in terms of initiating events and mitigating equipment failures caused by a fire. The fire initiated event sequences that need to be addressed were identified. Only a single, independent fire was assumed to occur in any plant location.

Based on the results of the study done all the fire compartments under consideration were categorized as the following groups:

- Compartments in which a fire may lead to a design basis initiating event in combination with a failure of a safety system train.
- Compartments in which a fire may cause a design basis initiating event without failures in safety systems.
- Compartments in which a fire may not lead to a design basis initiating event, but failures in safety systems are possible.
- Compartments in which a fire cannot affect safety related systems.

The fire hazard assessment validated that adequate plant system response is available to achieve a safe shutdown state following any postulated fire.

FIRE FREQUENCY

Insights gained from operational experience of all the 18 units with VVER-1000 reactors in Russia and Ukraine were used in the fire PSA as the statistical basis for establishing frequencies of fires as a function of the initiating fire source. The fire sources listed below were considered:

- turbine & generator facility;
- pumps;
- fans, compressors and HVAC units;
- diesel generators;
- motor operated valves;
- cables;

- board devices such as I&C cabinets and control panels;
- electrical equipment such as transformers, inverters, and rectifiers;
- circuit breakers;
- oil tanks;
- transient fuels.

Information on fire incidents that occurred during the period 1986 through 1999 was collected. A total of 201.8 calendar years, including 140.4 years of power operation, pertain to the observation period. The available information for each event was reviewed to estimate the frequency of future fires involving a given fire ignition source based on the occurrence rate of similar fires in the past. The frequencies presented in Table 1 were calculated on a "per plant basis".

Table 1. Frequency of fires at operating NPPs with VVER-1000

Equipment becoming an ignition source	Frequency of large fires per plant-year
Turbine, generator, exciter	2.9E-3
Turbine driven pump	8.3E-4
Motor driven pump, including oil ignitions	3.5E-3
Switchgear, including circuit breakers	1.4E-3
Electrical components (transformers and others)	1.4E-3
Cable	1.1E-2
Transient fuel	2.7E-4

It is important to note that since the mid-1980s substantial effort has been made to upgrade fire safety at VVER plants. This includes the application of fire retardant coatings on cables, upgrading of fire barriers, improved fire suppression systems, improved plant procedures and operator training, etc. Improvements to the VVER-1000 plants have likely contributed to a significant reduction in the potential for fires to significantly challenge nuclear safety [9]. Therefore the estimates presented in Table 1 can be considered as conservative ones for the current state.

Fire incident information gathered confirms the fact that fires at VVER-1000 plants are relatively rare, and those occurred were usually minor and had little or no safety significance. Therefore the fire occurrence frequency in compartments was estimated involving data on both fires and ignitions at VVER-1000 plants, which may be considered as precursors of fires. Probability of the ignition-fire transition was derived from operational experience.

The fire frequency estimation for each particular compartment was conducted on the basis of counting the number of individual ignition sources (a portion of the total mass – for cables). The resulting frequencies obtained for the particular equipment types from operational experience were assigned to the Kudankulam NPP compartments proportionally to the number of pieces of equipment in these compartments, i.e. these frequencies were weighted by the quantity and type of combustibles located in the compartment. Transient combustibles were also addressed.

PROBABILISTIC MODEL

The fire PSA relied on the plant response probabilistic model developed for the internal initiating events, which was modified to take into account fire-induced failures and impact of a fire on human actions. The fire risk model includes all equipment and cables required to support the functionality of the selected systems.

The event trees and fault trees were solved using the computer code RISKSPECTRUM, as used in the internal PSA. The methodology of this code is based on the method of small event trees / large fault trees widely used in the world practice.

The methodology for re-development of the event/tree fault tree models to represent fire scenarios includes the following steps:

- Review of any simplifications or approximations incorporated during the internal event PSA development to confirm their applicability for the fire risk assessment.
- Modification of the fault trees to include logic keys (house events) to enable fire induced plant failures to be modelled correctly.

- Incorporation of additional fire-induced events in the fire risk model.
- Review of the common cause failure modelling since the degree of redundancy in safety systems may be reduced as a consequence of the fire.
- Re-evaluation of human error probabilities modelled in the event trees and fault trees taking into account the impact of the fire on the operational scenarios represented.

The following assumptions were used in developing the fire probabilistic model:

- The plant is operating in its normal operating mode at power at the time of the fire.
- Fire need not be postulated to be coincident with independent, low frequency incidents in the plant, unless they are caused as a consequence of the fire.
- Components that fail safe after a damage by the fire can be credited as fulfilling their safety functions.
- Additional random failures are considered together with those directly attributable to the fire.
- Passive mechanical components, such as heat exchangers, valves, and pipes that may be exposed to a fire, remain structurally intact as a pressure barrier.
- The fire PSA used conservative assumptions and excluded credit for operator recovery actions for modelling the subject fire area. Any actions that require operators to enter to affected compartment were neglected. In the case of components not affected by the fire, the recovery of failed components could continue to be claimed.
- To account for the factor of a fire impact to operators, the post-accident human error probabilities were increased by a factor of 10 for any action in comparison with the PSA for internal initiating events except for the neglected actions.
- A mission time of 24 hours was used.

RESULTS

The overall fire-induced CDF for Kudankulam NPP was quantified to be 9.1E-9 per reactor year that is six times lower than the CDF addressed in the internal event PSA. Figure 1 shows the contributions to the total CDF from different fire-induced initiating events. Inadvertent openings of safety/relief valves were calculated to be dominant contributors. It was found that a fire-induced electrical fault (hot short) along the path of the connected power/control cables may cause the valve to inadvertently change position to the undesired open condition leading to the initiating event in the case of a fire. However, since the mechanisms leading to spurious actuation of equipment are not well understood, much uncertainties are associated with scenarios involving such failure modes. A detailed circuit analysis to identify the specific circuit faults causing the valve to change position will be performed at the detailed design stage.

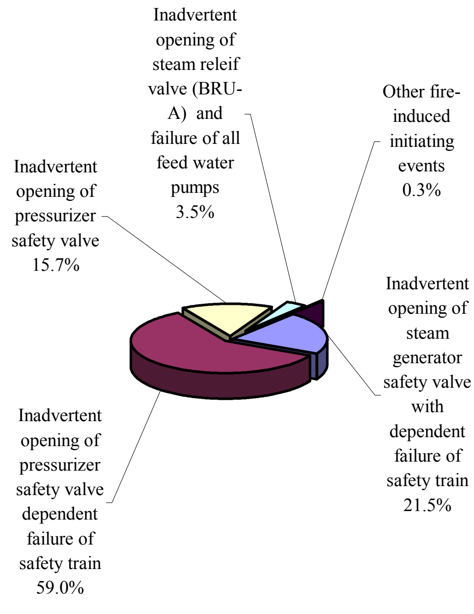

Figure 1. Proportional contribution to core damage frequency from fire-induced initiating events at Kudankulam NPP.

Contributions into the CDF from fires in different locations were also estimated. The largest contribution to the total CDF comes from fires in diesel generator buildings UKD and relevant cable tunnels UKZ. Accident sequences combining the inadvertent opening of a pressurizer safety valve with a failure of a safety system train contribute approximately 59% to the overall fire-induced CDF. Accident sequences involving inadvertent opening of a steam generator safety valve with its subsequent non-closing and a failure of one safety system train contribute 21.5% to the total fire-induced CDF.

Although the fire PSA was performed in a conservative manner the extremely low value of the CDF obtained shows that passive safety features incorporated in the design of Kudankulam NPP assure reliable fire resistance of the plant.

CONCLUSIONS

Results of the fire PSA demonstrate a strong possibility to achieve in the Kudankulam NPP design the probabilistic safety goals established for future plants [10].

Although the numerical results of the fire PSA are associated with large uncertainties at the PSAR design stage, the fire PSA including the fire hazard analysis can provide an extremely cost-effective approach to fire protection improvement.

References

1. Federal Authority of Nuclear Regulation. Main recommendations for performing PSAs for NPPs, RB-032-02, Russian Federation, Moscow, 2004 (in Russian).
2. International Atomic Energy Agency. Treatment of internal fires in probabilistic safety assessment for Nuclear Power Plants, Vienna, 1998.
3. International Atomic Energy Agency. Procedures for Conducting Probabilistic Safety Assessment of Nuclear Power Plants (Level 1), Vienna, 1992.
4. V.Morozov and G.Tokmachev. PSA for fires at VVER-1000/320 nuclear power plants. In: Proceedings of the TOPSAFE’98 International Conference held by the European Nuclear Society and the Spanish Nuclear Society in Valencia, Spain, April 15-17, 1998. Senda Editorial,S.A: CD-Rom "TOPSAFE'98 Papers".
5. J A Carretero, Y Shvyryaev, G Tokmachev, V Morozov, P Fernandez. Results of Novovoronezh-3 PSA performed within TACIS-91 Programme In: Proceedings of the TOPSAFE’98 International Conference held by the European Nuclear Society and the Spanish Nuclear Society in Valencia, Spain, April 15-17, 1998. Senda Editorial,S.A: CD-Rom "TOPSAFE'98 Papers".
6. V.Morozov, G.Tokmachev, M.A.Azarm, A.Minister. Probabilistic study of fire ifluence on Smolensk NPP safe shutdown capability. In: Proceedings of International Conference Fire&Safety 2001, held in London on 12-14 February, 2001: CD-Rom “Nuclear Engineering International, Conference documents, FIRE&SAFETY 2001, 12-14 February London”
7. V.B.Morozov, G.V.Tokmachev, A.Yu.Zhuravlev. Probabilistic and Deterministic Safety Assessments of NPPs with VVER-1000 reactors given a fire, All-Russian Conference «Practice of PSA development and their application for NPPs with VVER-type reactors both operating and under design”, 18-20 November 2002, Atomenergoproekt, Moscow
8. V.B.Morozov and G.V.Tokmachev. Analysis of impact of possible fires and their consequences on safe shutdown of VVER-1000 reactor unit. Teploenergetika (Rus) - Thermal Engineering (Engl), Moscow, 2005, No 1, Pages 47-50
9. S.P.Nowlen, M.Kazarians, N.Siu, H.W.Woods. Fire Risk Insights from Nuclear Plant Fire Incidents. In: Proceedings of International Conference Fire&Safety 2001, held in London on 12-14 February, 2001: CD-Rom “Nuclear Engineering International, Conference documents, FIRE&SAFETY 2001, 12-14 February London”
10. International Atomic Energy Agency. Basic Safety Principles for Nuclear Power Plants 75-INSAG-3 Rev.1 INSAG-12, Vienna, 1999