NUBIKI NUCLEAR SAFETY RESEARCH INSTITUTE

System Reliability Analysis and Probabilistic Safety Assessment to Support the Design of a New Containment Cooling System for Severe Accident Management at NPP Paks

Tamas Siklossy

siklossyt@nubiki.hu

PSAM 14
Probabilistic Safety Assessment & Management
16-21 September 2018, Los Angeles, USA

Content

- Background
- Objectives
- Different Analysis Areas
  - Specification of Quantitative System Reliability Target
  - System Reliability Analysis
  - Aggravating Effects of the Planned System on Plant Safety
- Conclusions

Background

- SAM upgrades implemented in Paks NPP (to prevent progression of SA sequences, ensure long-term stable state)
  - external cooling of the reactor vessel;
  - installation of passive autocatalytic recombiners for hydrogen removal during severe accidents;
  - reinforcement of the spent fuel pool cooling system against loss of coolant;
  - use of a dedicated diesel generator to supply power to severe accident management hardware components;
  - implementation of a dedicated instrumentation system for severe accident management.

NUBIKI

Background

- A severe accident management related proposal of the post-Fukushima Targeted Safety Reassessment (TSR) of Paks NPP:

  an independent containment heat removal system

  - last item in the series of severe accident management related technological improvements
  - to prevent containment overpressurization due to slow pressure build-up under severe accident conditions
  - to ensure containment integrity in case large amount of steam was generated due to external cooling of the reactor pressure vessel
  - provide water supply for external cooling of the reactor pressure vessel by condensing the steam generated thereof, and transferring the heat outside the containment

Objectives

- To support the design of the containment cooling system:
  - evaluate the adequacy of system design from reliability point of view – confronting:
    - quantitative system reliability requirements specified
    - system reliability analysis results
  - evaluate and assess the aggravating effects induced by the interconnection between two independent ECCS lines to provide redundancy in cooling water supply
- Scope – internal failures:
  - system reliability analysis: full power operation
  - change in CDF: LPSD states of a typical refueling outage

Specification of Quantitative System Reliability Target

NUBIKI

- Design specifications:
  - startup and system operation by operator actions in a manipulator containment -> no automatic actions
  - redundancy and diversity are not required
  - conservative assumptions on actual plant state and environmental conditions (a scenario specific analysis was out of the scope of the study)

U>0.1

- Effects of the system on the large release frequency
  - sensitivity assessment for all containment states defined in the Level 2 PSA by changing system unavailability in the model
  - how much risk (LRF) reduction can be achieved by the system

Specification of Quantitative System Reliability Target

NUBIKI

Containment State	Containment Cooling System Unavailability					
	0	**0.1**	**0.2**	**0.3**	**0.5**	**1**
Catastrophic Containment Failure, Rupture	$1.81 \cdot 10^{-8}$	$1.88 \cdot 10^{-8}$	$1.95 \cdot 10^{-8}$	$2.02 \cdot 10^{-8}$	$2.17 \cdot 10^{-8}$	$2.52 \cdot 10^{-8}$
Containment bypass	$4.09 \cdot 10^{-8}$	$4.09 \cdot 10^{-8}$	$4.09 \cdot 10^{-8}$	$4.09 \cdot 10^{-8}$	$4.09 \cdot 10^{-8}$	$4.09 \cdot 10^{-8}$
Early containment failure	$1.80 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$
Late containment failure	$7.92 \cdot 10^{-8}$	$1.42 \cdot 10^{-7}$	$1.97 \cdot 10^{-7}$	$3.09 \cdot 10^{-7}$	$4.63 \cdot 10^{-7}$	$6.66 \cdot 10^{-7}$
Increased late containment leakage	$6.00 \cdot 10^{-10}$	$5.51 \cdot 10^{-9}$	$1.04 \cdot 10^{-8}$	$1.53 \cdot 10^{-8}$	$2.51 \cdot 10^{-8}$	$4.97 \cdot 10^{-8}$
Late containment failure, containment spray system operates	$1.15 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$
Total	$\mathbf{3.30 \cdot 10^{-7}}$	$\mathbf{3.95 \cdot 10^{-7}}$	$\mathbf{4.59 \cdot 10^{-7}}$	$\mathbf{5.77 \cdot 10^{-7}}$	$\mathbf{7.42 \cdot 10^{-7}}$	$\mathbf{9.73 \cdot 10^{-7}}$
Large releases prevented in total	$\mathbf{6.43 \cdot 10^{-7}}$	$\mathbf{5.78 \cdot 10^{-7}}$	$\mathbf{5.14 \cdot 10^{-7}}$	$\mathbf{3.96 \cdot 10^{-7}}$	$\mathbf{2.31 \cdot 10^{-7}}$	**0.00**

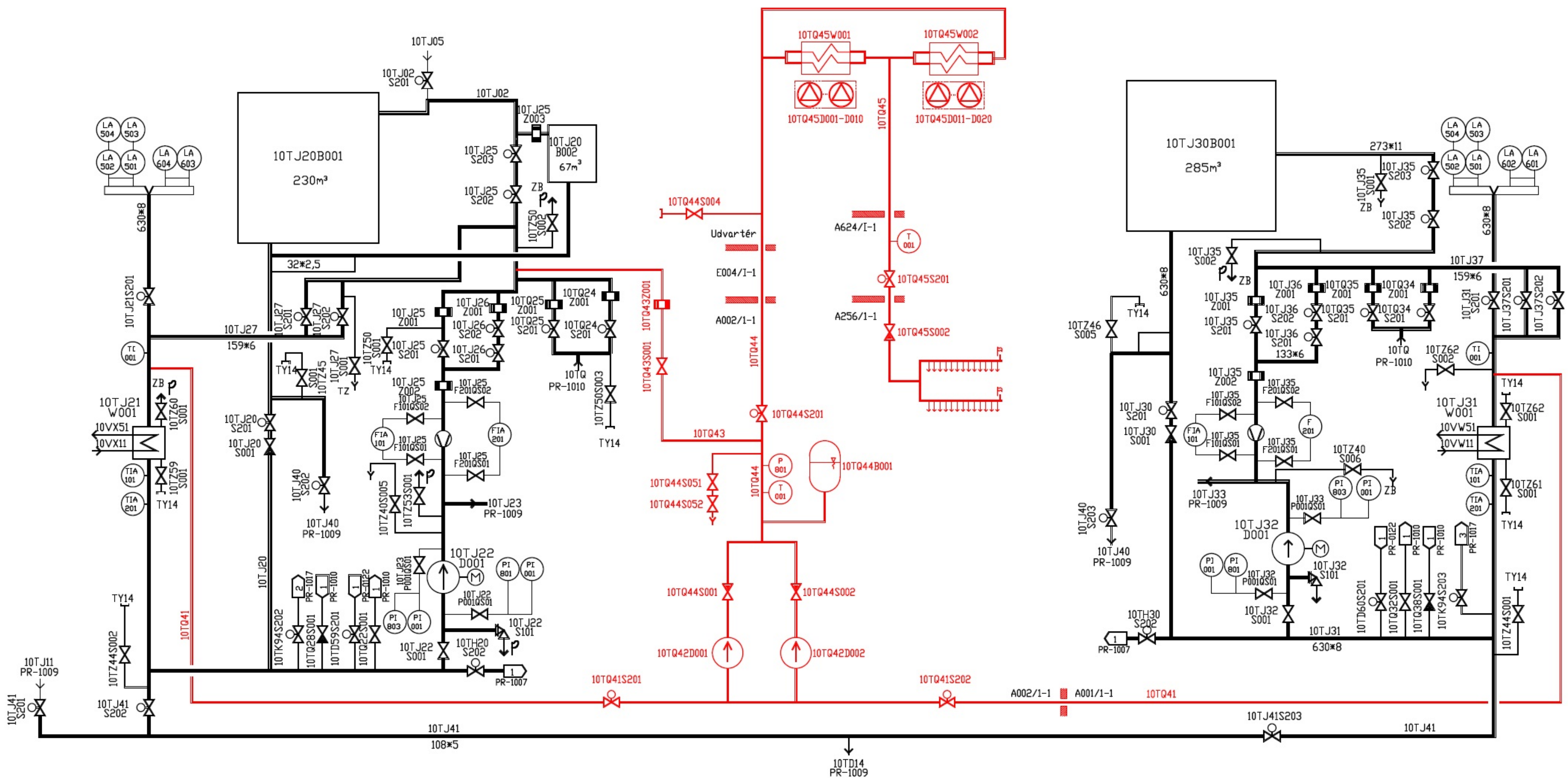
Specification of Quantitative System Reliability Target

NUBIKI

- Hungarian Nuclear Safety Code req. 3.2.4.0900.:
  „For all initial operating conditions and effects, excluding sabotage and earthquake, the aggregated frequency of severe accident event sequences resulting in large or early releases shall not exceed 10^{-5}/a. Besides, by all means of reasonable plant modifications and interventions, 10^{-6}/a shall be targeted."
- Considerations:
  - LRF for POSs with open containment: $1.82 \cdot 10^{-6}$/a -> LRF > 10^{-6}/a
  - realistic expectation to ensure an adequate level of safety enhancement
  - LRF that may be prevented by the system is $6.43 \cdot 10^{-7}$/a
  - 64,3% of the 10^{-6}/a value -> reduce this ratio considerably
  - probabilistic safety target for the system unavailability:
    - 0.3 (ratio reduction to 25%), but
    - 0.16 (ratio reduction to 10%) should be aimed at.

System Reliability Analysis

Preliminary P&ID of the cooling system at NPP Paks



System Reliability Analysis

- Definition of system function:
  The operation of the containment cooling system is successful, if the system ensures heat removal from the containment atmosphere for 168 hours so that containment overpressurization is prevented.
- System reliability model development and quantification
  - Fault tree analysis
  - Human reliability analysis (type A and type C human errors)
  - Modelling dependent failures
  - Reliability data assessment

System Reliability Analysis - HRA

Human actions:

- electric power supply from a dedicated SAM DG:
  - transportation of a mobile 6/0.4 kV transformer container,
  - setting up mobile cable interconnections and startup of the diesel generator.
- manual startup of the system from the manipulator containment,
- continuous control of system operation, changes in configuration.

SLIM was used, with the following PSFs:

- environmental conditions;
- time constraint / emergency stressor;
- task complexity;
- human-machine interface;
- training and qualification of personnel;
- teamwork;
- procedures.

System Reliability Analysis – Results and Evaluation

- Mean unavailability for the defined system function is 0.326 > 0.3
- Main risk contributors: Type C events + mechanical & electrical failures
- Sensitivity analysis:
  - SAM DG of the neighboring unit can be used (0.291)
  - fixed cable interconnection between SAM DG and container (0.237)
- Modifications based on lessons learned (see sensitivity analysis):
  - EOP and training important to system startup and operation
  - system should be powered by the safety 6 kV busbars if available
  - automatic actuations for system startup and operation
  - ensure the operation of the system from a location that is better protected against the effects of radioactive radiation

Aggravating Effects of the Planned System on Plant Safety

- Interconnection of the two ECCS lines (if valves unintentionally left open)
  - all possible interconnections (with false valve positions)
  - hydraulic characteristics determine the flow rate and direction through the interconnections
  - valves positions relevant to the flow directions of low pressure ECCS
  - the operability of pumps that can be affected by the flow paths due to mispositioned valves
- The only screened in event sequence: the water recirculated through the containment sump gets to a low pressure ECCS tank, fills the tank up, and then the coolant is lost by pouring on the floor of the ECCS room
- 8 scenarios interpreted in detail (6 of which for $T_{pr}>150°C$)

Aggravating Effects of the Planned System on Plant Safety

NUBIKI

- Modification of the PSA model – sump failure (fault tree level)
- Input data assessment – Type A human errors
- Findings – pre-initiator actions have a significant effect (RIF=6.2)

Initiating Event Groups	**CDF (1/a)**		**Change in CDF**	
	considering the modification	**neglecting the modification**	**1/a**	**%**
ABC	$1.112\cdot10^{-6}$	$1.113\cdot10^{-6}$	$1.118\cdot10^{-9}$	0.101
DE	$2.098\cdot10^{-6}$	$2.100\cdot10^{-6}$	$1.892\cdot10^{-9}$	0.090
FJLM	$9.866\cdot10^{-7}$	$9.866\cdot10^{-7}$	$9.300\cdot10^{-12}$	0.001
GHI	$6.513\cdot10^{-6}$	$6.513\cdot10^{-6}$	0.000	0.000
K	$9.432\cdot10^{-7}$	$9.432\cdot10^{-7}$	$1.390\cdot10^{-11}$	0.001
Total	$\mathbf{5.791\cdot10^{-6}}$	$\mathbf{5.794\cdot10^{-6}}$	$\mathbf{3.033\cdot10^{-9}}$	**0.052**

Conclusions

Safety assessment in support of the design of a new containment cooling system

- quantitative system reliability targets were specified
  - no strict requirement in the regulations
  - realistic expectation to ensure an adequate level of safety enhancement
- system reliability analysis was performed
  - system unavailability (0.326) slightly exceeds the target (0.3)
  - after design modifications the pre-defined probabilistic target can be met
- aggravating effects of the interconnection between the ECCS lines on ECCS functionality and Level 1 PSA result
  - negligible increase in CDF
  - sensitivity and importance measures for Type A human errors related to leaving valves unintentionally open are significant

Thank you for your attention!

This work has been greatly supported by the National Research, Development and Innovation Fund in the frame of the VKSZ_14-1-2015-0021 Hungarian project.