Simulation-based analysis of reliability and availability for the Vessel Cooling System in the High Temperature Engineering Test Reactor: Implications for safety and profitability

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

Mina Torabi

Division of Nuclear Energy and Environmental Studies

Mina.Torabi@ncbj.gov.pl

Fundusze Europejskie
Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska
Europejski Fundusz Społeczny

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Introduction

- The Vessel Cooling System (VCS) is an active cooling system of HTTR that supplies cooling during normal operation to cool the biological shield around the Reactor Pressure Vessel (RPV), and removes residual heat from both the core and RPV during no forced cooling accidents.

- Failure of the VCS during normal operation would result in the emergency shutdown of the reactor and the unplanned outage of the cogeneration facility, which increases its total Forced Outage Rate (FOR) factor.

- The VCS unavailability during the LOFC event might not pose an immediate threat to nuclear reactor safety, but it may influence the accident consequences, including increased deterioration of the RPV and biological shielding.

- The aim of this work is to determine the life-cycle reliability and availability characteristics of the VCS during both normal operation and emergency conditions.

Objectives

- Identification and exploration of reliability data on industrial plant equipment to determine VCS component reliability models by analysing failure rate distribution and repair time range.
- Investigation of the frequency and severity of VCS component failures using Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA).
- Determination of the life-cycle reliability and availability characteristics of VCS, corresponding to the system requirements during normal operation and LOFC.
- Evaluation of the impact of VCS failures on the Forced Outage Rate (FOR) of the HTTR-based electricity-hydrogen cogeneration plant.
- To create and compare different reliability and availability models of the VCS, representing its parallel- and single-unit mode of operation.

Vessel Cooling System

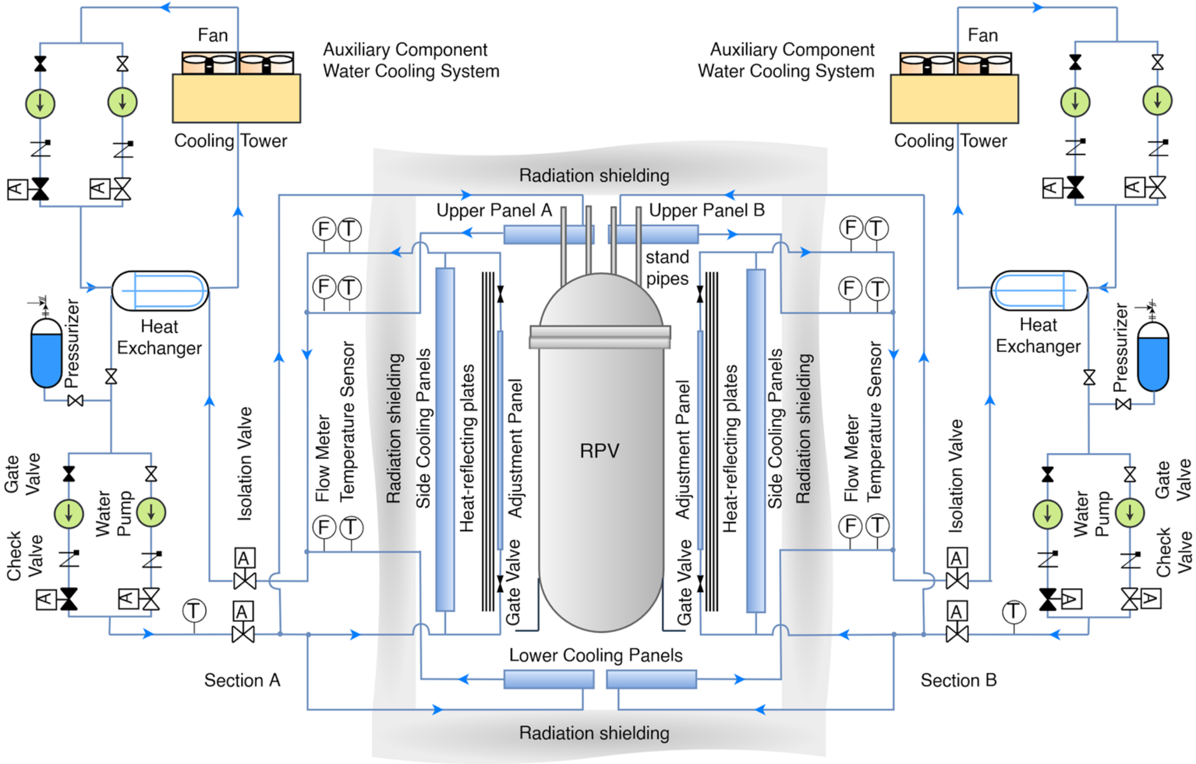

Fig. 1: Diagram of the VCS System of HTTR [Created based on: Kunitomi K, et al., 1996, Saikusa A, et al. 2003]

Vessel Cooling System

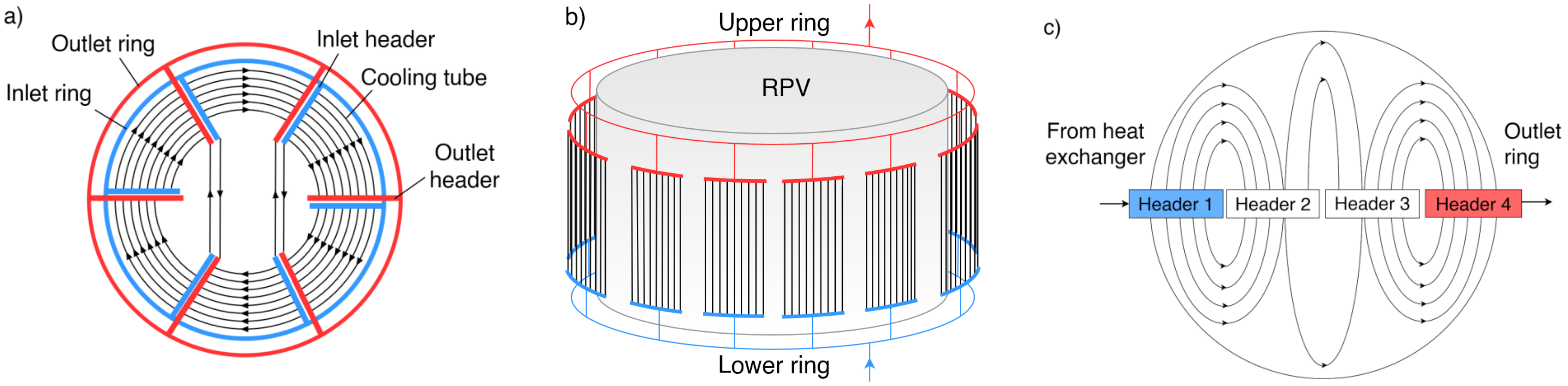

Fig. 2. Schematic flow diagram of a single section's VCS panels: (a) upper panel, (b) side panel, and (c) lower-bottom panel [Created based on: A. Saikusa, , et al., , 2002.]

Data investigation

Aim of data investigation :

- Identify and explore databases on industrial equipment failures
- Determine the reliability models for VCS components by failure rate distribution and repair time range

Problem with input data selection:

- Lack of information about specific equipment,
- incompleteness, heterogeneity, or multiplication of existing data sources.

Datasets used for analysis:

- Industry-average data from US nuclear power plants by Idaho National Laboratory (INL, 2021) - Majority of data
- Reliability data for research reactors issued in 2021 by International Atomic Energy Agency (IAEA) - Supplementary dataset.
- Data of the Power Reliability Enhancement Program by the US Army (PREP, 2001) - To specify failure rate of water supply pipes and CWPs' tubes.
- Reliability data for Gas Cooled Reactors by General Atomic (GA, 1978) - Main source of component repair times
- Report on maintenance and repair times of equipment in technological facilities by INL (2012) - Supplementary dataset

Data investigation

Tab. 1. Reliability models of the VCS components (λ – failure rate, /h – per hour, /d – per demand, τ – repair time).

No.	Component	Failure Mode	λ_{mean}	$\lambda_{5\%}$	$\lambda_{95\%}$	τ_{mean}	$\tau_{5\%}$	$\tau_{95\%}$
1	Cooling Tower	Fan fails to run	5.18E-06/h[27]	2.36E-06/h[27]	8.94E-06/h[27]	40h[30]	4h[30]	130h*
		Fan fails to start	6.07E-04/d[27]	7.85E-05/d[27]	1.74E-03/d[27]			
2	CWP Tubes	Leakage (per meter)	4.39E-09/h[29]	2.010E-09/h*	8.030E-09/h*	168h**	72h**	320*
3	Heat Exchanger	Leakage external	1.90E-07/h[27]	5.71E-09/h[27]	6.08E-07/h[27]	30h[30]	4h[30]	92h*
		Leakage internal	2.76E-07/h[27]	2.21E-07/h[27]	3.36E-07/h[27]			
		Tubes plugging	3.39E-07/h[27]	1.11E-09/h[27]	1.32E-06/h[27]			
4	Pressurizer	Leakage external	4.18E-07/h[27]	5.99E-10/h[27]	1.72E-06/h[27]	40h[30]	8h[30]	108h*
5	Valve (Check)	Fails to open	1.12E-05/d[27]	4.39E-08/d[27]	4.29E-05/d[27]	24h[30]	3h[30]	74h*
		Leakage external	4.34E-09/h[27]	1.34E-09/h[27]	8.72E-09/h[27]			
		Leakage internal	7.25E-08/h[27]	5.76E-08/h[27]	8.88E-08/h[27]			
		Spurious close	6.20E-10/h[27]	2.44E-12/h[27]	2.38E-09/h[27]			
6	Valve (Gate)	Fails to open	1.69E-02/d[28]	5.81E-03/d[28]	3.84E-02/d[28]	24h[30]	3h[30]	74h*
		Leakage	1.14E-05/h[28]	3.90E-06/h[28]	2.61E-05/h[28]			
		Spurious close	1.05E-06/h[28]	5.40E-08/h[28]	4.99E-06/h[28]			
7	Valve (Motor)	Fails to open	3.43E-04/d[27]	7.80E-05/d[27]	7.62E-04/d[27]	24h[30]	3h[30]	74h*
		Leakage external	1.88E-08/h[27]	4.85E-11/h[27]	7.43E-08/h[27]			
		Leakage internal	3.61E-08/h[27]	7.97E-11/h[27]	1.44E-07/h[27]			
		Spurious operation	2.54E-08/h[27]	1.93E-08/h[27]	3.23E-08/h[27]			
8	Valve (Relief)	Fails to control	8.20E-09/h[27]	3.22E-11/h[27]	3.15E-08/h[27]	24h[30]	3h[30]	74h*
		Leakage external	8.20E-09/h[27]	3.22E-11/h[27]	3.15E-08/h[27]			
		Leakage internal	3.85E-07/h[27]	2.64E-07/h[27]	5.25E-07/h[27]			
		Spurious operation	7.38E-08/h[27]	2.73E-08/h[27]	1.39E-07/h[27]			
9	Water Piping	Leakage (per meter)	2.16E-09/h[29]	9.880E-10/h*	3.950E-09/h*	30h[30]	2h[30]	106h*
10	Water Pump	Leakage external	1.98E-07/h[27]	3.16E-09/h[27]	6.80E-07/h[27]	53h[31]	2h[31]	200h*
		Fails to run	2.26E-06/h[27]	3.94E-07/h[27]	5.38E-06/h[27]			
		Fails to start	5.88E-04/d[27]	1.09E-04/d[27]	1.38E-03/d[27]			

* Calculated assuming Log-Normal distribution, ** Estimated based on engineering judgment.

FMEA and FTA of VCS Component

- FMEA measured failure modes in terms of severity and occurrence
- FMEA was limited to consideration of severity and occurrence due to lack of information
- FTA combined failure modes to calculate failure probability for each component
- Frequency of failures was measured in probability per year of system operation

FMEA of VCS

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FMEA Severity Scale:

1. No detectable effect - VCS system fully operated (e.g., deterioration of the monitoring system, failure of temperature/pressure sensor, or flow meter).
2. Loss of redundancy on a single VCS section (e.g., cooling water pump and valves in a parallel configuration).
3. Loss of a single VCS section with a failure located outside the reactor containment vessel (e.g., failure of a heat exchanger, pressurizer, cooling fan, or piping).
4. Loss of a single VCS section with a failure located inside the reactor containment vessel (e.g., water supply pipes and CWPs' tubes).
5. Loss of both VCS sections due to a common cause failure (e.g., loss of electrical power, loss of both cooling towers located in the same building, leakages caused by the degradation of the CWPs' welds)

FTA of VCS Component

- The cooling tower had the highest probability of failure in one year
- The second most likely event is the failure of the side cooling panel
- Medium values of failure probability were achieved for the heat exchanger and pressurizer
- The lowest failure probability was achieved for the piping inside the containment vessel and the pump sections.

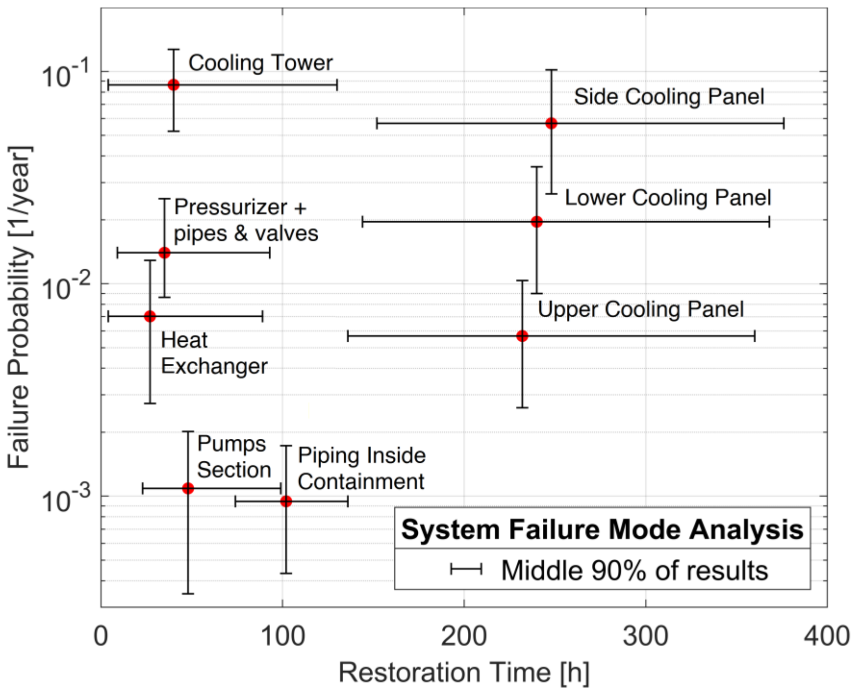

Fig. 3. One-year failure probability and restoration time for a VCS section (the components include the associated valves).

Reliability and Availability Analysis

- ***Objectives:***

- Determination of the life-cycle reliability and inherent availability of the VCS system in normal operation ($A_{Inher.}$) and emergency condition ($A_{Emerg.}$).

- Determination of the 20-years availability of the HTTR-based cogeneration plant ($A_{Cogen.}$) decreased by accounting for downtime caused by VCS failures.

- Assessment of the contribution of the VCS failures to the FOR_{VCS} of the HTTR-based cogeneration plant versus the industry standards.

- To create and compare alternative models of VCS reliability and availability, including a parallel-unit mode (both sections at 100% flow rate) and a single-unit mode (one section on standby).

- Quantify the frequency of VCS failure during LOFC accidents (λ_{VCS}^{LOFC}).

Foundations of Analysis

- The component reliability model associated with each failure mode i:

$$R_i(t) = e^{-\lambda_i t}$$

- The system reliability was modeled by a two-parameter Weibull function:

$$R_{VCS}(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

- The inherent availability ($A_{Inher.}$) of the VCS system under normal operation was defined as:

$$A_{Inher.} = \frac{SH_{VCS(2/2)}}{SH_{VCS(2/2)} + CM_{VCS(2/2)}}$$

Foundations of Analysis

- The system availability during the emergency conditions was estimated as follows:

$$A_{Emerg.} = \frac{SH_{VCS(1/2)}}{SH_{VCS(1/2)}+CM_{VCS(1/2)}}$$

- The lifetime availability of the HTTR-based cogeneration plant can be determined as:

$$A_{Cogen.} = \frac{SH_{Cogen.}}{SH_{Cogen.} + PM + FOH_{\{S_1,\dots,S_n\}}}$$

Foundations of Analysis

- The Forced Outage Rate of the plant resulting from the VCS system failures was then defined as follows:

$$FOR_{VCS} = \frac{FOH_{VCS}}{SH_{Cogen.} + FOH_{VCS}} 100\%$$

- The frequency of events when the VCS failure occurs during the LOFC accident was estimated as:

$$\lambda_{VCS}^{LOFC} = \lambda^{LOFC} \left(1 - A_{Emerg.} \cdot R_{VCS}(T_{LOFC}|T)\right)$$

Simulation Models

- Two models for VCS system operation have been simulated based on the VCS system requirements using Reliability Block Diagrams (RBDs) :

A. Parallel-unit operation mode (Model 1) : Both VCS sections are required in normal operation with all cooling panels active except for adjustment tubes. Failure of a single section or significant deterioration of cooling panels results in an immediate reactor scram.

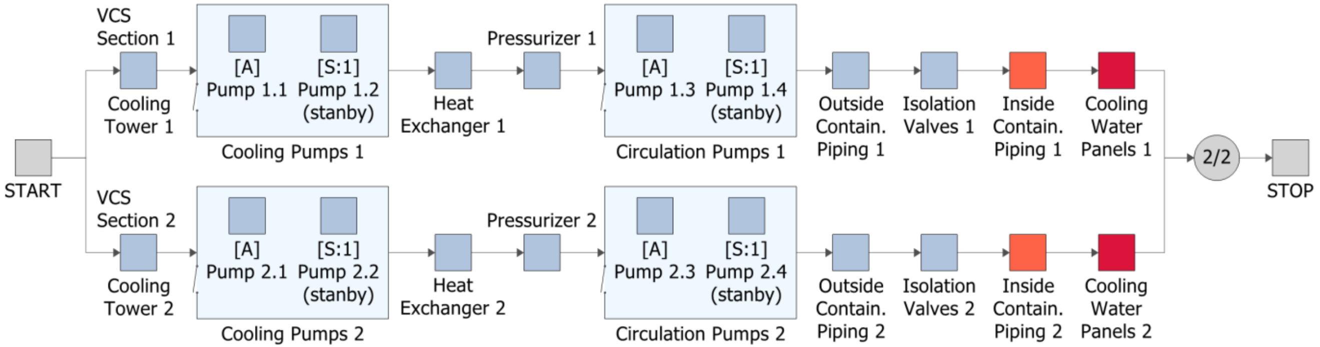

Fig. 4. Reliability Block Diagram corresponding to the parallel-unit operation mode of the VCS system (Model 1).

B. Single-unit operation mode (Model 2) : Although VCS has been designed to run with both sections in normal operation, a single-unit operation is possible with one section continuously running and the other in standby condition. Failure of the active section results in the activation of the standby one.

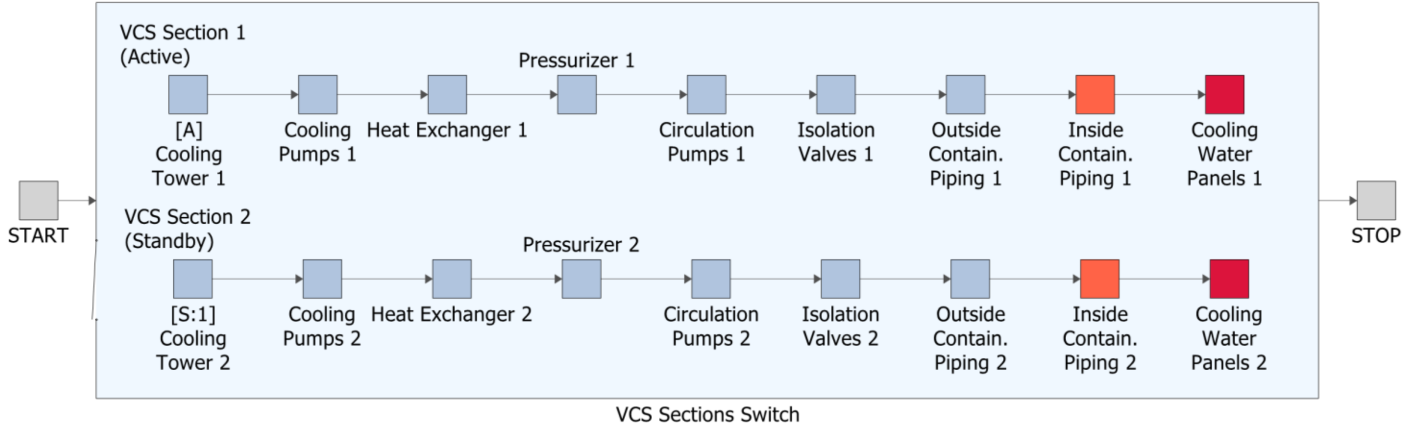

Fig. 5. Reliability Block Diagram corresponding to the single-unit operation mode of the VCS system (Model 2).

Results

- The presented case shows that the failure of Pump 1.1 (section 1) and Pump 2.1 (section 2) occurred in months 98 and 112, respectively, but did not cause system downtime as standby pumps were activated successfully.

- A long system outage occurred in month 108 due to the failure of the cooling panel in Section 1, which required the reactor to be cooled down prior to repair.

- A short system downtime occurred in month 118 due to the failure of the cooling tower repaired without waiting for the reactor to cool down.

- The time needed for restart after VCS failures, preventive maintenance, and refueling was not taken into account as the inherent characteristics of VCS system reliability and availability were modeled.

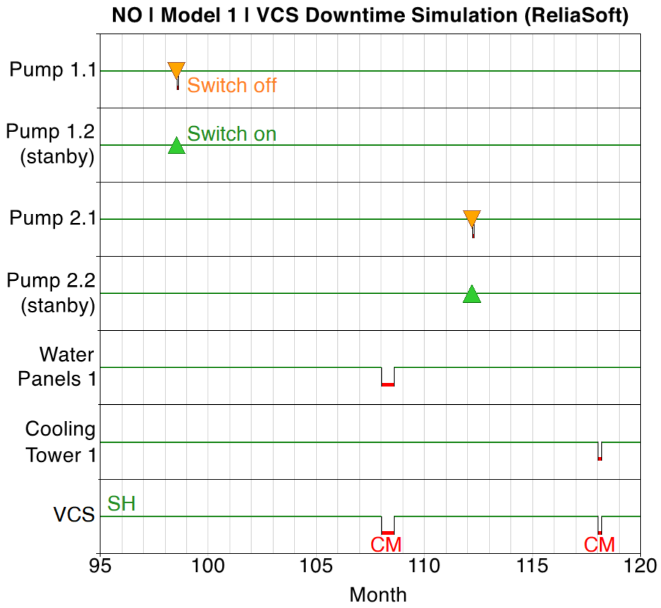

Fig. 6. Exemplary simulation of outages for the VCS system operating in the parallel-unit mode (Model 1).

Results

- Establishing a measure of uncertainty - the simulations were run using three consistent failure rates used: optimistic ($\lambda_{5\%}$) , pessimistic ($\lambda_{95\%}$), and mean values, Component repair times and forced outage times considered.

- The life-cycle reliability of the VCS in normal operation follows an approximately exponential trend.

- The Weibull reliability functions fitted to the simulation points give values of β parameter ranging from 1.00 (base case) to 1.13 (LB).

- The failure rate during normal operation, λ_{VCS} (2/2), can be assumed constant and calculated as the inverse of η parameter.

- The upper bound of reliability gives a failure rate of 3.56E-05/h, the base case gives 4.64E-05/h, and the lower bound gives 5.95E-05/h.

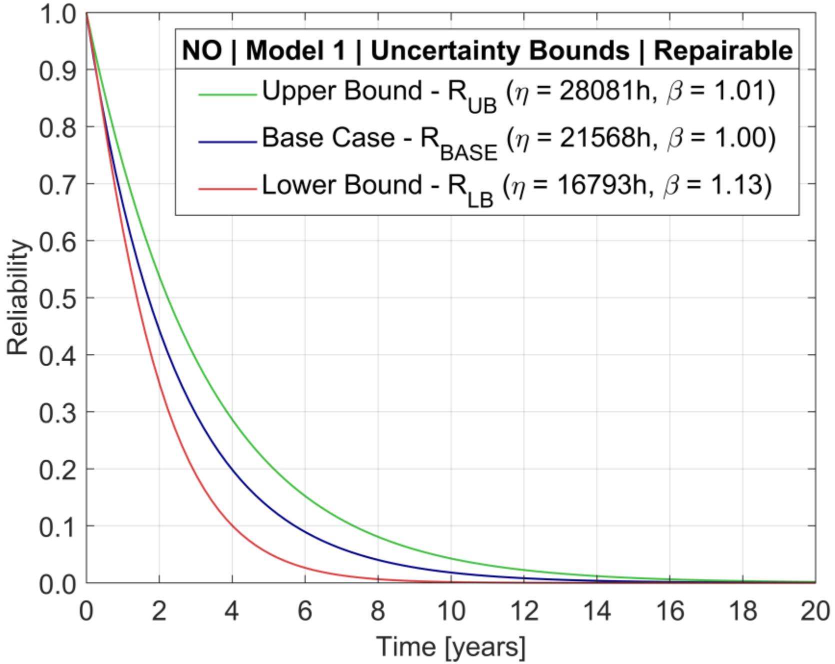

Fig. 7. Life-cycle reliability of the VCS system determined for the parallel-unit mode (Model 1) under normal operation.

Results

- The mean values of the experimental distributions for UB, base case, and LB are respectively 99.56%, 99.46%, and 99.21%.

- Results suggest potential for improvement in system operability.

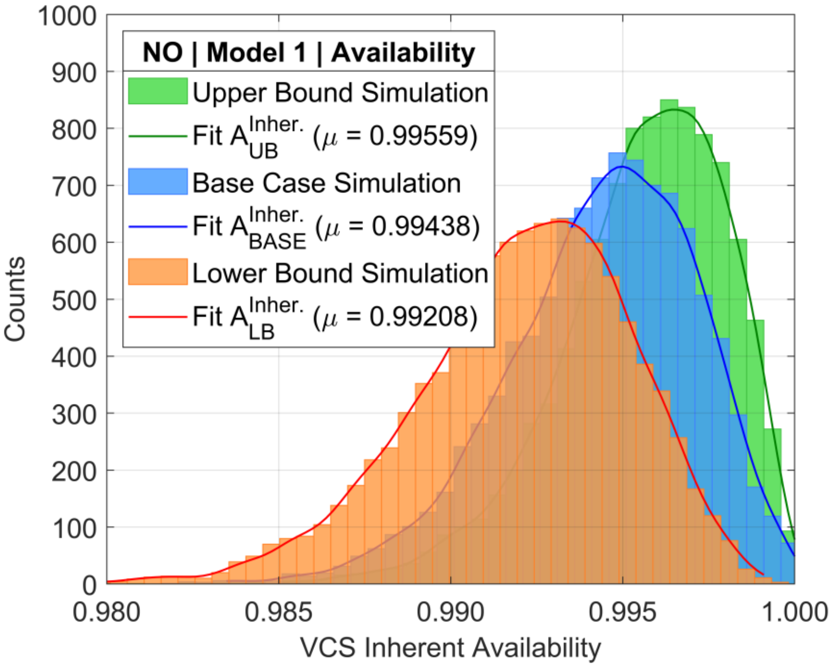

Fig. 8. Inherent availability of the VCS system determined for the parallel-unit mode (Model 1) under normal operation

Results

- The emergency VCS sections also show an approximately exponential character with β values ranging from 1.02 to 1.19.
- The system failure rate λ_{VCS} (1/2) : 9.90E-08/h (UB), 1.40E-07/h (BASE), and 4.53E-07/h (LB).
- The mean availability : 99.9995% (UB), 99.9992% (base case), and 99.9984% (LB).
- The VCS performs excellently in removing residual heat from the reactor core and RPV after the LOFC accident.

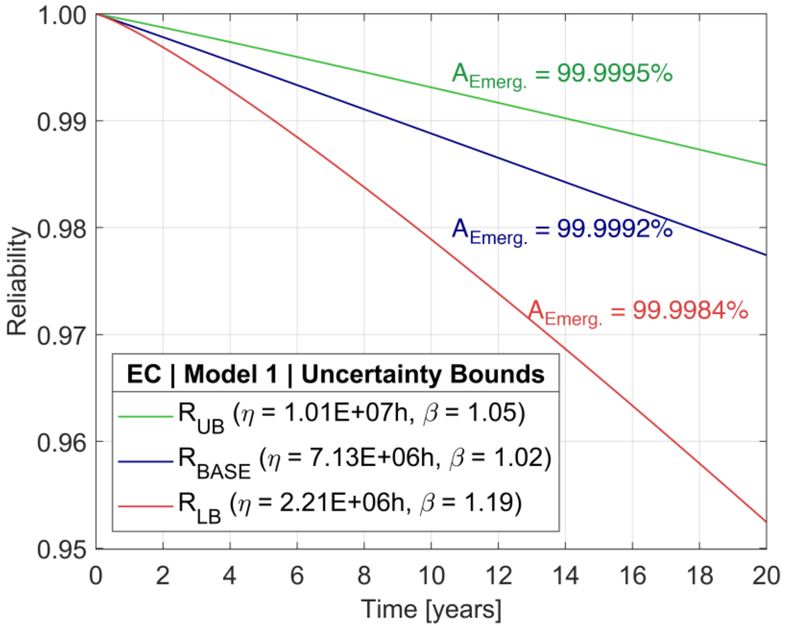

Fig. 9. Life-cycle reliability of the VCS system determined for the parallel-unit mode (Model 1) corresponding to the emergency conditions (one of two VCS sections is required).

Results

Objective: VCS failures do not reduce the availability of the HTTR-based cogeneration plant ($A_{Cogen.}$) below an acceptable level.

- Simulations includes downtime for reactor cooldown, corrective maintenance, restart after VCS restoration (FOH), and refueling/preventive maintenance (PM).

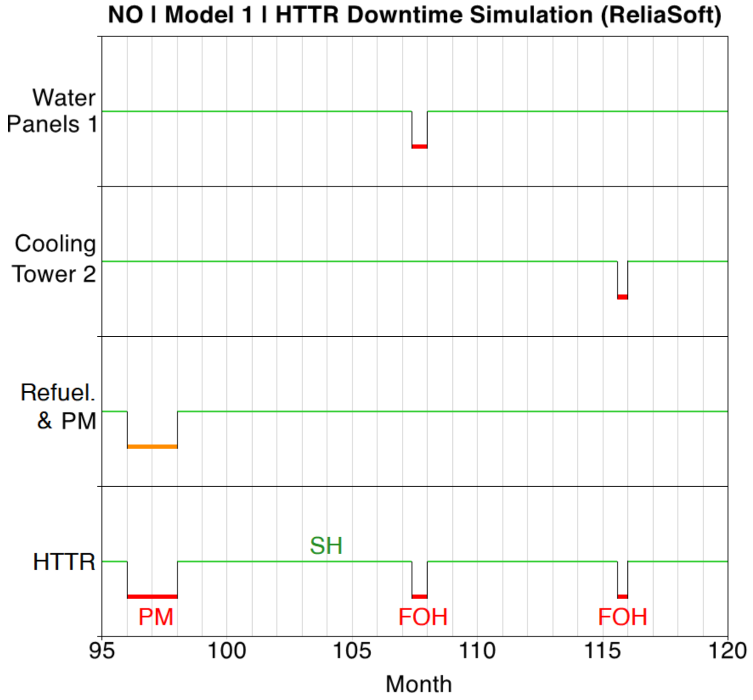

Fig. 10. Exemplary simulation of the HTTR outages caused by the VCS failures and scheduled maintenance (Model 1).

Results

- The mean value of cogeneration plant availability is reduced by VCS failures and preventive maintenance to below 91.5% for the upper bound and remains below 91% for the lower bound, with a range of variability from 90 to 92%.
- The majority of the simulation results for FOR_{VCS} are located between 1 and 2% for all cases.
- Need for improvement of VCS system performance under normal operating conditions (Comparison of FOR_{VCS} factor with nuclear industry standards).
- Average annual rates of FOR from U.S. nuclear power plants used as reference. Range of total FOR values obtained in the frame of ITP is between 1% and 3%, with values lower than 2% dominating the statistics.
- FOR_{VCS} of HTTR is 1.5% and $FOR_{Electrical}$ is 2%, exceeding the limit from the NRC standards by the impact of only two systems of HTTR, Electrical and VCS.

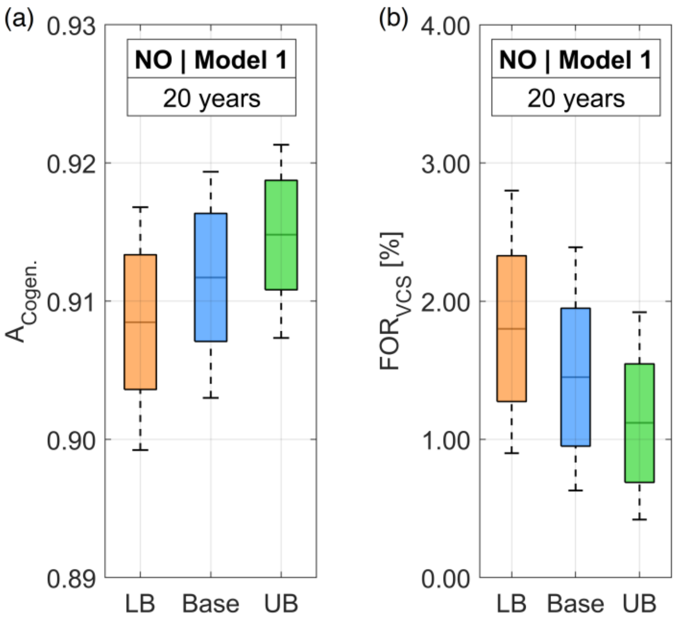

Fig. 11. Simulation results for HTTR-Based Cogeneration Plant in parallel-unit VCS mode (a) Availability ($A_{Cogen.}$) (b) Forced Outage Rate (FOR_{VCS})

Results

- Changing the operational mode of the VCS from parallel to single-unit can lead to a significant improvement in the *FOR*.

- Reliability curves shows an exponential character, with the failure rate ranging from 6.94E-07/h to 4.46E-06/h.

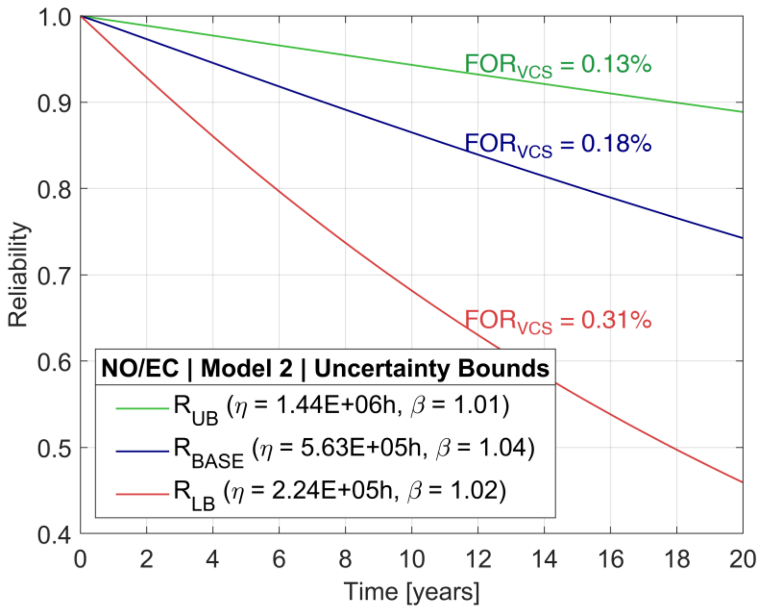

Fig. 12. Life-cycle reliability of the VCS system determined for the single-unit mode (Model 2) under normal operation.

Results

- Simulation results showed that the use of the single-unit mode results in increased availability of the cogeneration plant by over 1% to 1.5% due to the saved operating hours.
- However, the mean values of $A_{Emerg.}$ decreased to 99.97% - 99.82%, as well as an increased frequency of simultaneous occurrences of the LOFC accident and VCS failure (λ_{VCS}^{LOFC}).

Tab. 2: Comparison of the simulation results for the parallel-unit mode of the VCS (Model 1) and its single-unit mode (Model 2).

Simulation Case	Model 1				Model 2			
	$A_{Cogen.}$ [%]	FOR_{VCS} [%]	$A_{Emerg.}$ [%]	λ_{VCS}^{LOFC} [1/y]	$A_{Cogen.}$ [%]	FOR_{VCS} [%]	A_{Emerg} [%]	λ_{VCS}^{LOFC} [1/y]
Upper Bound	91.4812	1.12	99.9995	5.614E-09	92.4744	0.13	99.9720	8.063E-08
Base Case	91.1709	1.45	99.9992	9.359E-09	92.4367	0.18	99.9303	1.966E-07
Lower Bound	90.8475	1.80	99.9984	1.620E-08	92.3343	0.31	99.8173	5.220E-07

Results

- Single-unit VCS operation reduces FOR factor towards meeting industry standards.
- However, decreasing FOR factor reduces system availability to remove residual heat after an LOFC accident, which may raises regulatory concerns.
- Decision on accepting this mode of operation depends on country regulations, with several aspects to consider:
  - VCS safety classification recently degraded from Class 1 to Class 2, with no fuel degradation expected after LOFC accident and failure of both VCS sections.
  - Acceptable frequency of aircraft collisions with reactor is 1E-07/year, which is similar to λ_{VCS}^{LOFC} for Model 2, posing a greater risk to structural integrity.
  - Simultaneous LOFC accident and VCS failure frequency for Model 2 is lower than CDF and LERF acceptance criteria for LWR, despite conservative data used in simulations.

Summary and Concluding Remarks

- Long-term reliability and availability are essential for the industrial feasibility of HTGR-based cogeneration plants.
- Optimization of these parameters includes component quality, system design, and operating conditions.
- Optimization of the plant's reliability and availability may decrease resilience for emergency events in systems performing safety functions used in normal operation.
- Risk-informed decisions on system design and operating conditions are recommended in such cases.
- The HTTR's VCS was analyzed in terms of the life-cycle reliability and availability of the nuclear-based cogeneration plant.

Summary and Concluding Remarks

- The parallel-unit mode of the VCS operation under normal conditions exposes the cogeneration plant to a forced outage rate exceeding the nuclear industry standards.
- The single-unit VCS mode of operation significantly improves the forced outage rate, but reduces system availability toward emergency conditions, and increases the frequency of events when the VCS failure occurs during the LOFC accident.
- The resultant frequency of the VCS failure during the LOFC accident was compared with the risk criteria established for nuclear power plants, revealing the considered frequency is one or two orders of magnitude lower than the acceptance criteria for core damage frequency and the large early release frequency established for light water reactors.
- The simulation approach presented can contribute to the optimization of system design and operating strategy, and improve the PSA studies for HTGRs toward more realistic results.

Thank you

for your attention

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Mina Torabi

Division of Nuclear Energy and Environmental Studies

Mina.Torabi@ncbj.gov.pl

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