FMEA and reliability studies for the HTTR Vessel Cooling System

Mina Torabi

Division of Nuclear Energy and Environmental Studies

Mina.Torabi@ncbj.gov.pl

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Fundusze Europejskie Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska Europejski Fundusz Społeczny

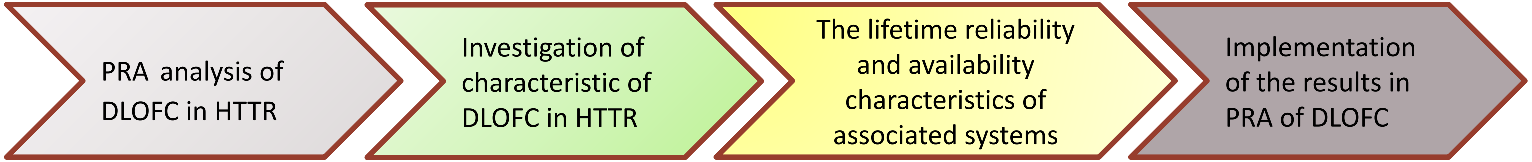
New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17

My PhD Thesis

- Probabilistic Risk Assessment of High Temperature Gas Cooled Reactor During DLOFC accident

- Supervisor: Professor Mariusz Dąbrowski
- Co-supervisor: Dr Karol Kowal

The roadmap of Ph.D.:



Introduction

- The Vessel Cooling System (VCS) is an engineered safety systems of HTTR that supply cooling during the normal operation and under no forced cooling accidents.
- The failure of the VCS is selected as one of the Anticipated Operational Occurrence (AOO)s that can cause the reactor scram; Thus, this was selected to be included in Failure Mode and Effect Analysis (FMEA) and reliability analysis.
- The lifetime reliability and availability of VCS has been analysed. The system Fault Trees and Reliability Block Diagrams have been created based on insights from the FMEA
- The results of this work can be implemented in safety and profitability of the future HTTR-based cogeneration plant

Goals

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- ✔ Collecting and investigating reliability data of the VCS components
- ✔ Providing potential failure mode analysis of the VCS components based on the FMEA framework
- ✔ Investigation of the system reliability and availability in normal and accident conditions

Vessel Cooling System

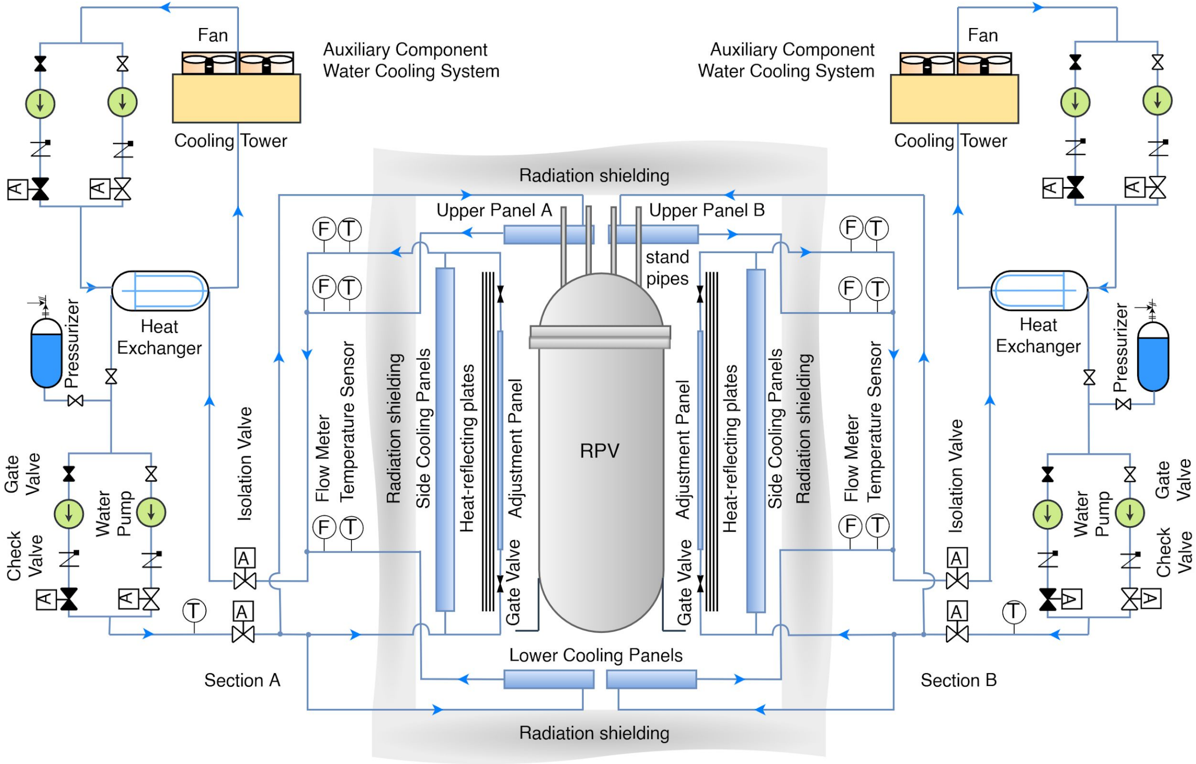


Fig. 1: Vessel Cooling System of HTTR [Created based on: Kunitomi K,et al., 1996, Saikusa A, et al2003]

VCS Cooling Panels

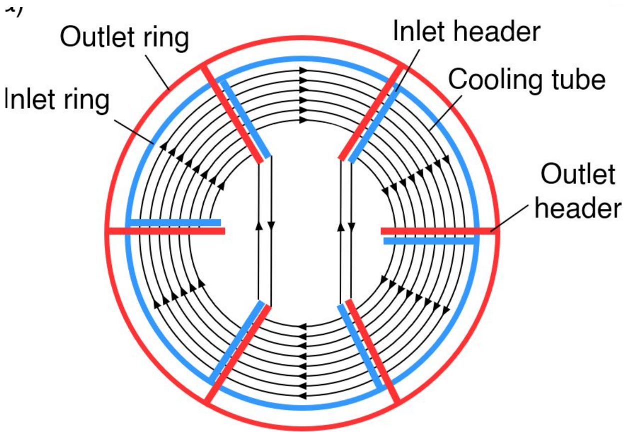


Fig. 2: Upper Panel

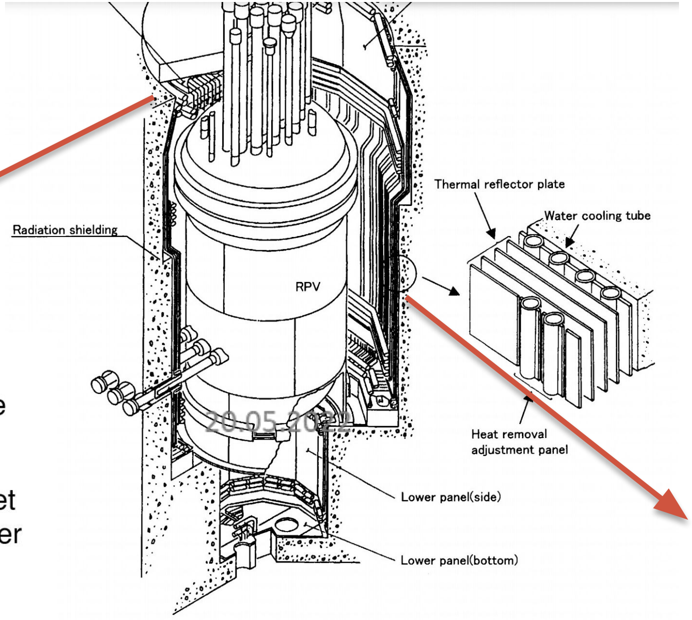


Fig. 3: Cooling Panels of VCS (Akio S, et al., 2005)

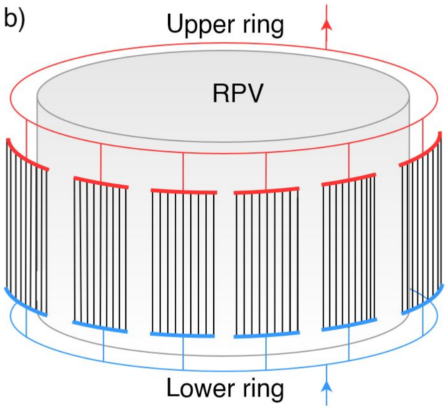
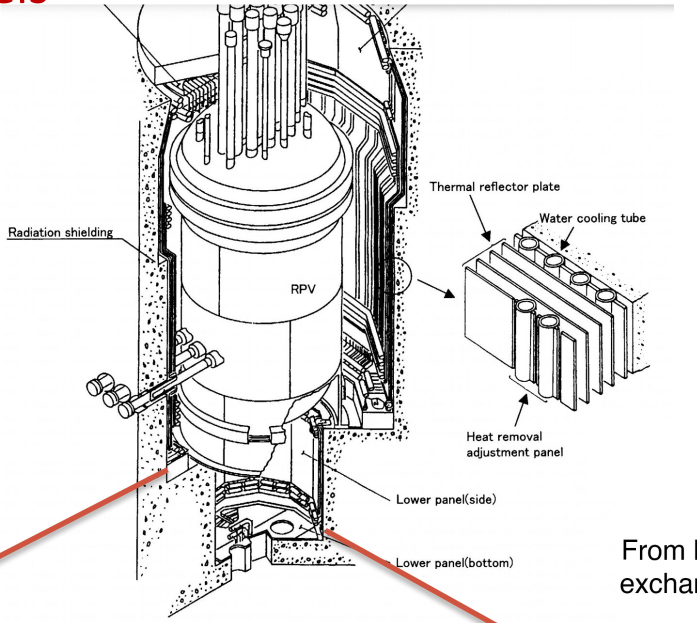


Fig. 4: Side Panel

VCS Cooling Panels



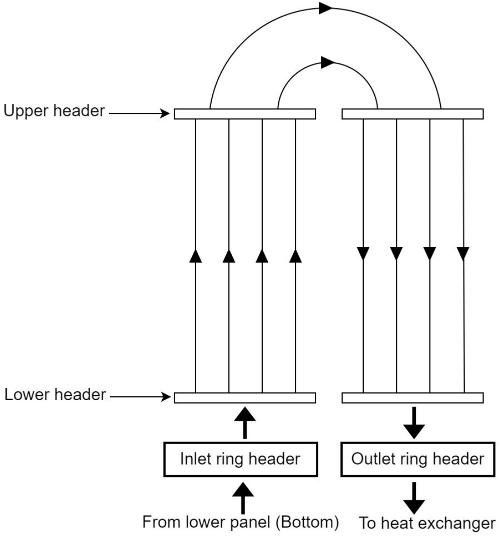


Fig. 5: Lower Panel (side)

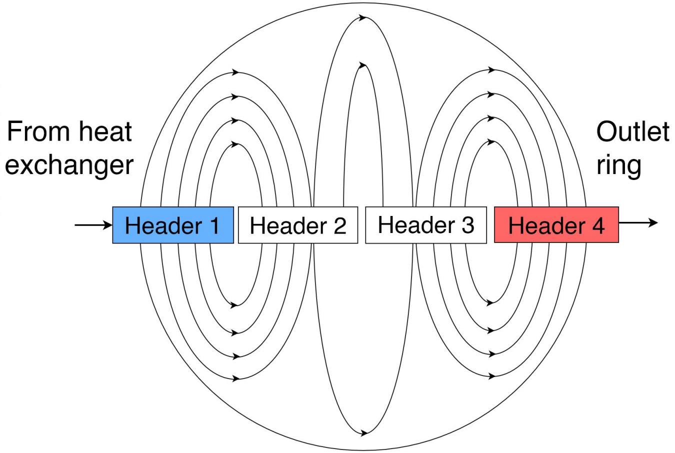


Fig. 6: Lower Panel (bottom)

Failure of VCS during DLOFC

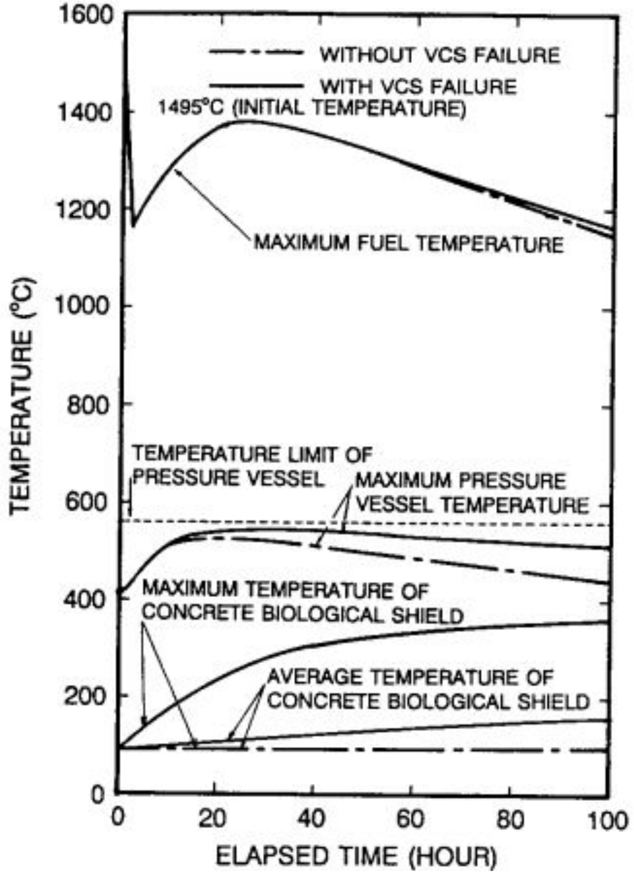


Fig. 7: Temperature transients with and without VCS failure (Akio S, et al., 2005)

VCS Components reliability data set

Component Type	Failure Mode(s)	λmean[1/hour	λ5%[1/hour]	λ50%[1/hour]	λ95%[1/hour]	Data source	Repair time						Data Sources of repair time
							Minimum	Mean	Maximum	5%	50%	95%	
Circulation Water Pump	Fail To Start, Normally Standby	7.94E-04	1.59E-04	6.78E-04	1.83E-03	NUREG/CR-6928	2 hr	53 hr	240 hr	–	–	–	mes forComponents inTechnologic
	Fail To Run, Early Term	1.22E-04	3.94-06	7.86E-05	3.89E-04								
	Fail To Run, Late Term	1.15E-05	1.35E-07	6.28E-06	4.07E-05								
	External Leakage (Small)	2.91E-07	9.46E-09	1.87E-07	9.22E-07								
	External Leakage (Rupture)	2.04E-08	2.18E-12	4.97E-09	9.32E-08								
	Fail to Start, Normally Running	1.08E-03	2.61E-04	9.52E-04	2.37E-03								
	Fail to Run, Normally Running	3.79E-06	1.15E-06	3.43E-06	7.68E-06								
Water Cooling Pipe	Piping Service Water System External	6.89E-10	2.71E-12	3.14E-10	2.65E-09	NUREG/CR-6928	–	–	–	2 hr	4 hr	8 hr	mes forComponents inTechnologic
	Piping Service Water System External	1.38E-10	1.48E-14	3.36E-11	6.30E-10								
	Clogged/Plugged/Blocked	5.14E-08	1.92E-09	1.98E-08	1.86E-07	Data set of							
Cooling Tower Fan	Fails To Start (Standby)	3.70E-04	2.34E-04	3.62E-04	5.31E-04	NUREG/CR-6928	epair Time Range:1.47 hr to 84/1 h			–	23.62 hr	–	mes forComponents inTechnologic
	Fail To Run <1H (Standby)	1.12E-05	4.42E-08	5.11E-06	4.32E-05								
	Fail To Run >1H (Standby)	2.33E-06	5.35E-07	2.03E-06	5.17E-06								
	Fails To Start	5.58E-04	6.54E-05	4.40E-04	1.45E-03								
	Fails To Run	2.33E-06	7.22E-07	2.12E-06	4.69E-06								
Heat Exchanger	Heat Exchanger Plugging/Heat Transfer	3.85E-07	2.32E-09	1.88E-07	1.44E-06	NUREG/CR-6928	48 hr						mes forComponents inTechnologic
	Internal Leakage (Small)	3.73E-07	5.03E-10	1.42E-07	1.54E-06								
	Internal Leakage (Rupture)	7.46E-09	7.98E-13	1.82E-09	3.41E-08								
	External Leakage (Small)	2.79E-07	9.77E-09	1.82E-07	8.81E-07								
	External Leakage (Rupture)	4.19E-08	4.48E-12	1.02E-08	1.91E-07								
	Heat Exchanger Plugging Non Standby	5.33E-07	5.34E-10	1.92E-07	2.22E-06								
Pressurizer (Surge tank)	Tank Rupture	2.61E-07	1.62E-07	2.55E-07	3.79E-07	NUREG/CR-6928	–	–	–	0.01 hr	0.03 hr	0.1 hr	mes forComponents inTechnologic
	Pressurized Liquid Tank Small Leakage	3.31E-07	1.22E-09	1.49E-07	1.28E-06								
	Pressurized Liquid Tank Large Leakage	2.32E-08	2.48E-12	2.65E-09	1.06E-07								
Gate valve (undefined actuator)	All failure modes	6.14E-06	3.06E-07	5.96E-07	2.53E-05	Report-ENS-2.3.4.2-T50-06	–	4 hr	–	0.5 hr	1 hr		mes forComponents inTechnologic
	Leakage/Rupture	5.57E-07	2.23E-07	4.80E-07	1.02E-06								
	Fails to Open/Close	3.79E-05	8.85E-06	3.50E-05	7.14E-05								
	Fails to Open/Close	3.79E-05	8.85E-06	3.50E-05	7.14E-05								
	Fails to Open/Close	3.79E-05	8.85E-06	3.50E-05	7.14E-05								

FMEA Analysis – Severity Rating

tab.1. FMEA rating scale for severity (S)

S	Description	Reactor shutdown needed	Cooling capability effect	Downtime (h)
1	Deterioration of a single redundant component of system A or B	No	No effect	-
2	Degradation of a single redundant component of system A or B	No	No effect	-
3	Loss of functionality of a single redundant component system A or B	No	No effect	-
4	Deterioration of a single non-redundant component of system A or B	Yes	No immediate effect	Up to 2 weeks
5	Deterioration of a single non-redundant component of system A or B	Yes	No immediate effect	More than 2 weeks
6	Degradation of a single non-redundant component of system A or B	Yes	Reduced cooling capability of system A or B	Up to 2 weeks
7	Degradation of a single non-redundant component of system A or B	Yes	Reduced cooling capability of system A or B	More than 2 weeks
8	Loss of functionality of a single non-redundant component of system A or B	Yes	Loss of system redundancy	Up to 2 weeks
9	Loss of functionality of a single non-redundant component of system A or B	Yes	Loss of system redundancy	More than 2 weeks
10	Loss of system A and B (common cause failure)	Yes	Loss of cooling capability	To be determined

1-3	The partial and complete loss of redundant items of systems A or B
4-9	The partial and complete loss of a single non-redundant component of system A or B
10	The complete failure of VCS due to loss of systems A and B

FMEA Analysis – Detection Rating

tab.2. FMEA rating scale for Detection (D)

D	Likelihood	Detection Method	Early Symptom	Visibility
1	Almost certain	Monitoring by direct sensor devices	Yes	Visible
2	Very High	Monitoring by direct sensor devices	Yes	Iinvisible
3	High	Monitoring by direct sensor devices	No	Visible
4	Moderately High	Monitoring by direct sensor devices	No	Iinvisible
5	Moderate	Monitoring by indirect sensor devices	Yes	Visible
6	Low	Monitoring by indirect sensor devices	Yes	Iinvisible
7	Very Low	Monitoring by indirect sensor devices	No	Visible
8	Minor	Monitoring by indirect sensor devices	No	Iinvisible
9	Very Minor	Lack of detection method	No	Visible
10	Neglected	Lack of detection method	No	Iinvisible

Very early stage of detection of component failure. These indicate the potential failure detection by direct installed flow or temperature sensor which provides the most immediate and direct diagnosis performance of the failure

The ability of VCS for identification of a failure occurrence of a particular component by indirect sensor and indicator devices within the main circulation systems A and B

The failure modes which are the most unlikely in terms of detection possibility. Since the system has not been equipped with an appropriate indicator to detection of such failure modes

FMEA Analysis – Occurrence Rating

tab.2. FMEA rating scale for Occurrence (O)

O	Description	Range of λ [1/h]	Nearest P
1	Ext. Low	$\lambda \leq$ 1E-09	p $\leq$ 5th
2	Very Low	1E-09 < $\lambda \leq$ 4E-09	5th – 10th
3	Low	4E-09 < $\lambda \leq$ 1E-08	10th – 15th
4	Mod. Low	1E-08 < $\lambda \leq$ 1E-07	15th – 36th
5	Moderate	1E-07 < $\lambda \leq$ 1E-06	36th – 68th
6	Mod. High	1E-06 < $\lambda \leq$ 1E-05	68th – 84th
7	Increased	1E-05 < $\lambda \leq$ 4E-05	84th – 86th
8	Increased	4E-05 < $\lambda \leq$ 1E-04	86th – 88th
9	Very High	1E-04 < $\lambda \leq$ 2E-04	88th – 90th
10	Ext. High	2E-04 < λ	90th < p

Occurrence/Severity Matrix

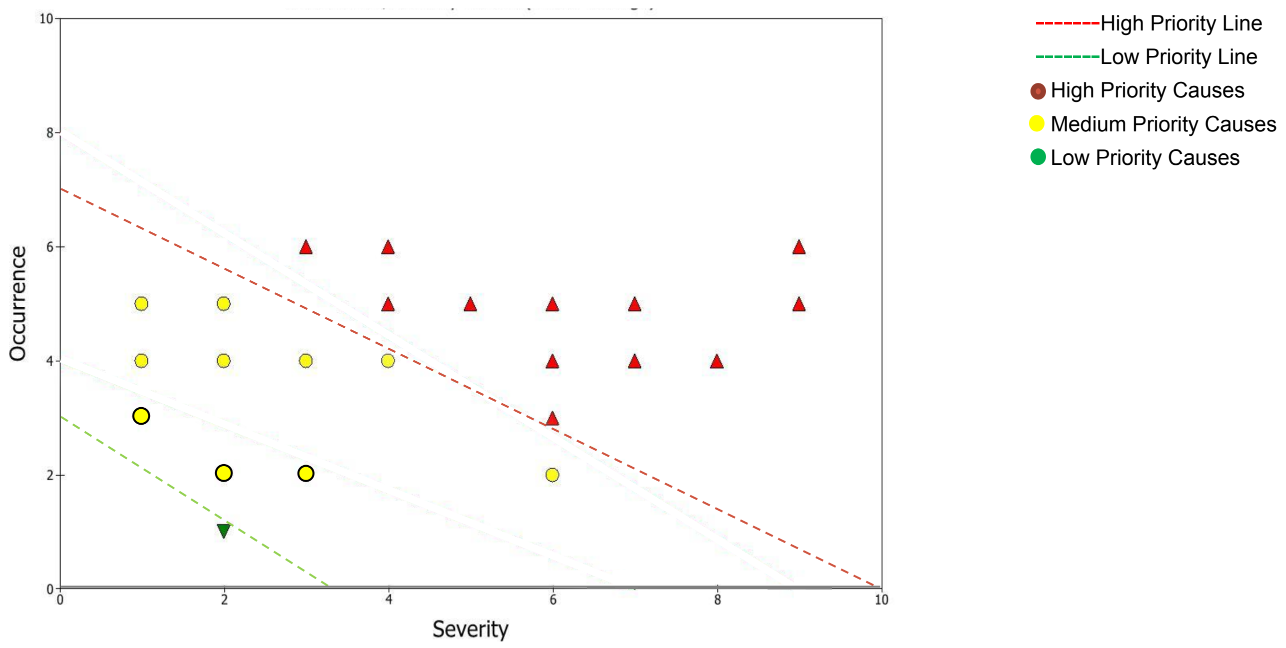


Fig. 8: Occurrence/Severity Matrix plot

The Highest Priority Causes: Failing to Run of Fan Sev = 9, Occ = 6 , D = 7 , RPNi = 378

Reliability and Availability assessment of the system

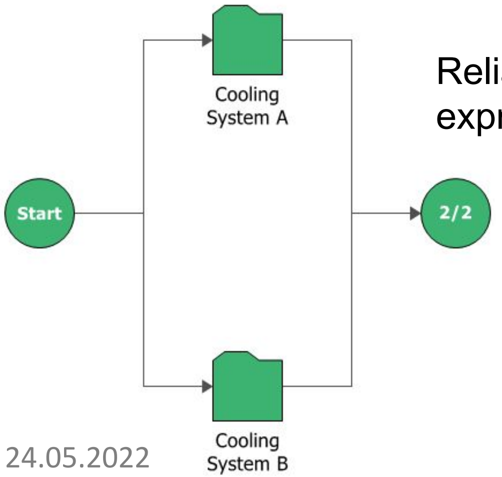
Two study Cases:

1) Operation of Both A and B system, considering failure of one system

2) Operation of Both A and B system, considering failure of both systems

Reliability for each component i:

$$R^{\text{Exp}}_{\text{mean}(i)} = e^{-\lambda_{\text{mean}(i)} t}$$



Reliability of components with redundant standby (the first *n* terms of the Poisson expression):

$$R_{\text{system}} = e^{-\lambda t}(1 + \lambda t)$$

Availability: $$A = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF}$$

Reliability and Availability Assessment of the system

First year metrics points simulation (Case 1)

Simulation Results	
Mean Availability	0.99265
Reliability at 8760 hr:	0.8207

Last year metrics points simulation (Case 1)

Simulation Results	
Mean Availability	0.99245
Reliability at 175200 hr:	0.0177

First year metrics points simulation (Case 2)

Simulation Results	
Mean Availability	0.993781
Reliability at 8760 hr:	0.845

Last year metrics points simulation (Case 2)

Simulation Results	
Mean Availability	0.993477
Reliability at 175200 hr:	0.0322

Block Downtime

Component Downtime: The total amount of time that the component is down

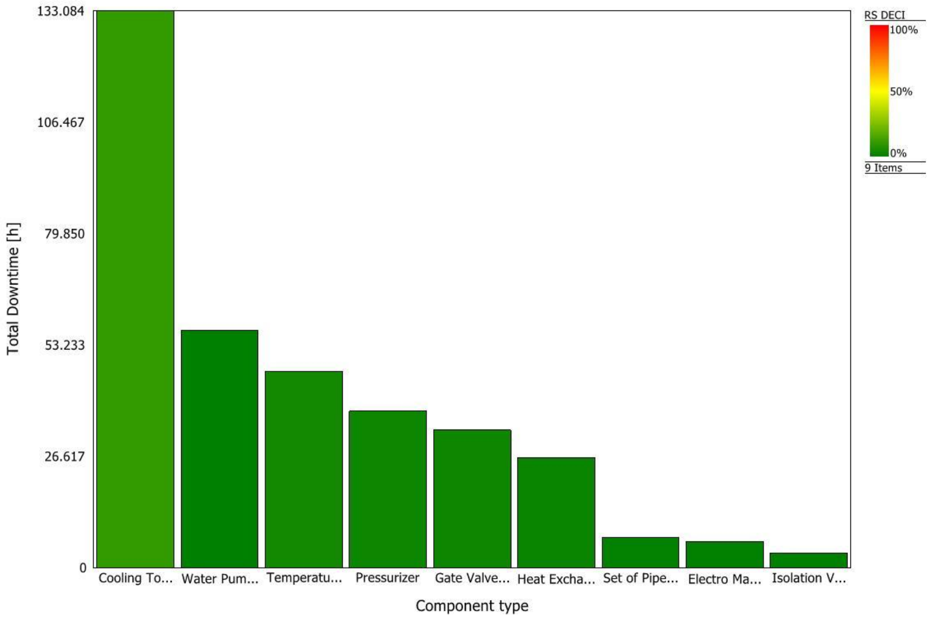


Fig. 9: Block Downtime of VCS components

RS DECI of Cooling Tower fan: 0.101

Lifetime Reliability Assessment of the system

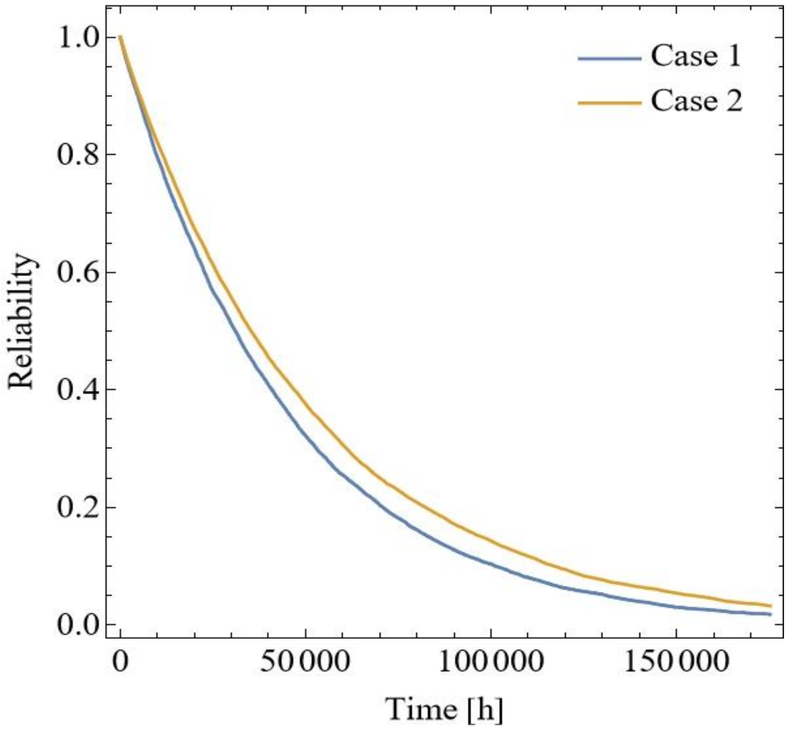


Fig. 10: Lifetime reliability of the HTTR VCS for the cases 1&2

Uncertainty assessment of the lifetime reliability of the system (Case 1)

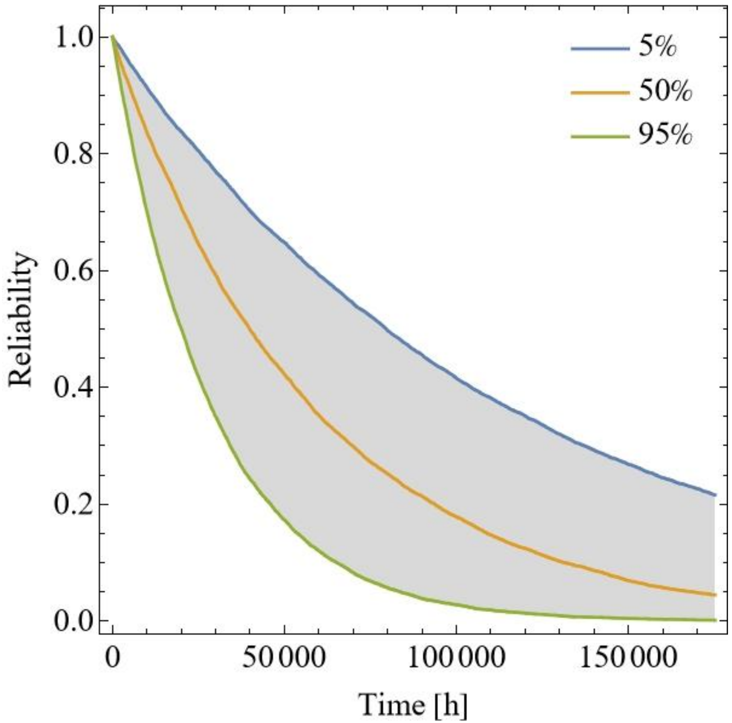


Fig. 12: Uncertainty of lifetime Reliability of the HTTR VCS for two considered cases

Summary

- The reliability data of the VCS components were collected and investigated
- FMEA analysis was performed to identify potential failure modes of HTTR VCS
- The identified failures were ordered then by their initial frequency and severity. Based on this ranking an O/S matrix was developed aiming at the failures categorization and identification of the most critical component
- The system Fault Trees (FT), and Reliability Block Diagrams (RBD) were developed based on the insights from the Failure Mode and Effect Analysis (FMEA) considering two significant cases : 1) Failure of one system 2) Failure of both systems
- The primary results indicate high availability and acceptable lifetime reliabilirty of the VCS under both situations
- Uncertainty assessment of reliability was performed for the case 1

Literature

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[2] Kunitomi, K. et al., Design and Fabrication of Reactor Vessel Cooling System (VCS) in HTR, Proceedings of the 3rd JAERI Symposium on HTGR Technologies, February 1996, Oarai, Japan.

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[8] KUNIYOSHI T, et al., A Rapid Evaluation Method of the Heat Removed by a VCS before Rise-to-Power Tests

Thank you

for your attention

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