Probabilistic Safety Assessment for High Temperature Gas-cooled Reactors

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

Introduction

- High Temperature Gas-cooled Reactors (HTGRs) : advanced energy solutions
- HTGR Advantages: Higher efficiency, improved safety features
- Thorough safety assessment essential for HTGR deployment
- Probabilistic Safety Assessment (PSA) as a key aspect of safety assessment
- **Traditional PSA methods developed for Light Water Reactors (LWRs) do not fit HTGRs**
- Overcome limitations of traditional PSA methodologies through a new approach tailored to HTGRs' unique safety-related system features and operational conditions

Research motivation

- Standard PSA methodology, originally developed for LWRs does not reflect specific design of HTGRs

- Key differences between HTGRs and LWRs necessitate the development of a new method:

Continuous operation of safety-related systems of HTGRs:

In HTGRs, some safety-related systems such as **electrical system** and **vessel cooling system** operate continuously.

- Traditional fault tree analysis assumes on-demand activation with specific mission time
- Ageing phenomena are more significant in continuous operation, impacting reliability assessments

Importance of repair and maintenance :

- Safety-related systems in HTGRs are repaired upon failure, leading to reactor scram
- In contrast, LWR safety systems remain on standby, with repairs not considered in fault tree analysis calculations

Advanced analytical tools:

- The Minimal Cut-Sets Upper Bound approximation, often used in PSA software for LWRs, may lack precision

Research objectives and hypothesis

- **Objective:** Improving PSA methodology to be applicable for HTGR
- **Hypothesis:** The application of life-cycle reliability and availability simulations instead of standard fault tree method can improve the standard PSA methodology by taking into account realistic operational conditions of HTGR safety systems
- **Case Study :** In High Temperature engineering Test Reactor (HTTR) the electrical system and vessel cooling system as a reference systems, Depressurized Loss of Forced Coolant (DLOFC) accident as a referential initiating event (DLOFC is one of the most severe design basis accidents in HTGRs , in HTTR it is assumed to be caused by the simultaneous rupture of both the concentric inner and outer primary hot gas duct)

Extending Failure Mode and Effect Analysis (FMEA) methodology for HTGR

- **FMEA**: A systematic approach to identify potential failures in a component, system, or process, and their causes and effects using 3 indications : Severity (S), Occurrence (O), and Detection (D)

- RPN = S x O x D

- **S** stands for **Severity**, which is a measure of how severe the effect of a failure mode is on the system.
- **O** stands for **Occurrence**, which is a measure of how frequently the failure mode occurs.
- **D** stands for **Detection**, which is a measure of how easily the failure mode can be detected.

- Proposing new approach in FMEA for two critical safety-related systems: electrical system and vessel cooling systems

Electrical system

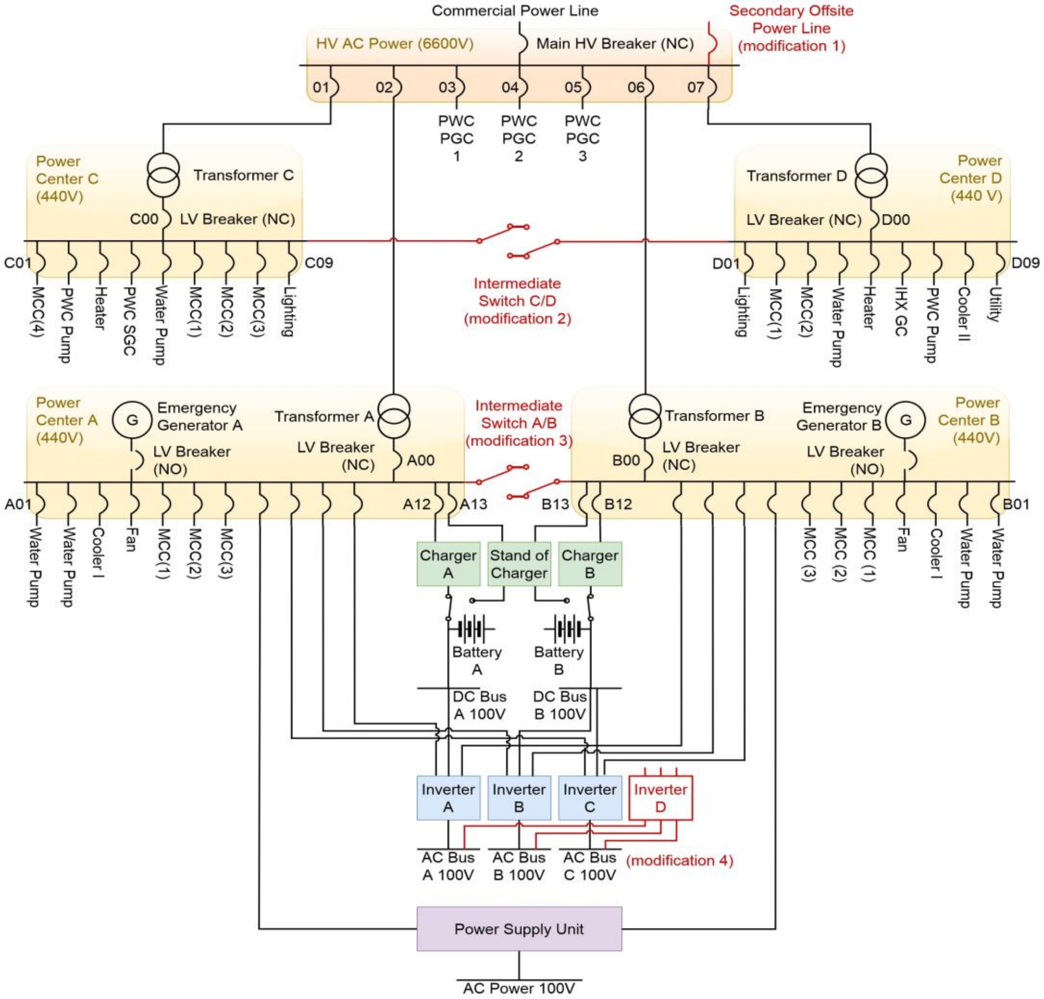
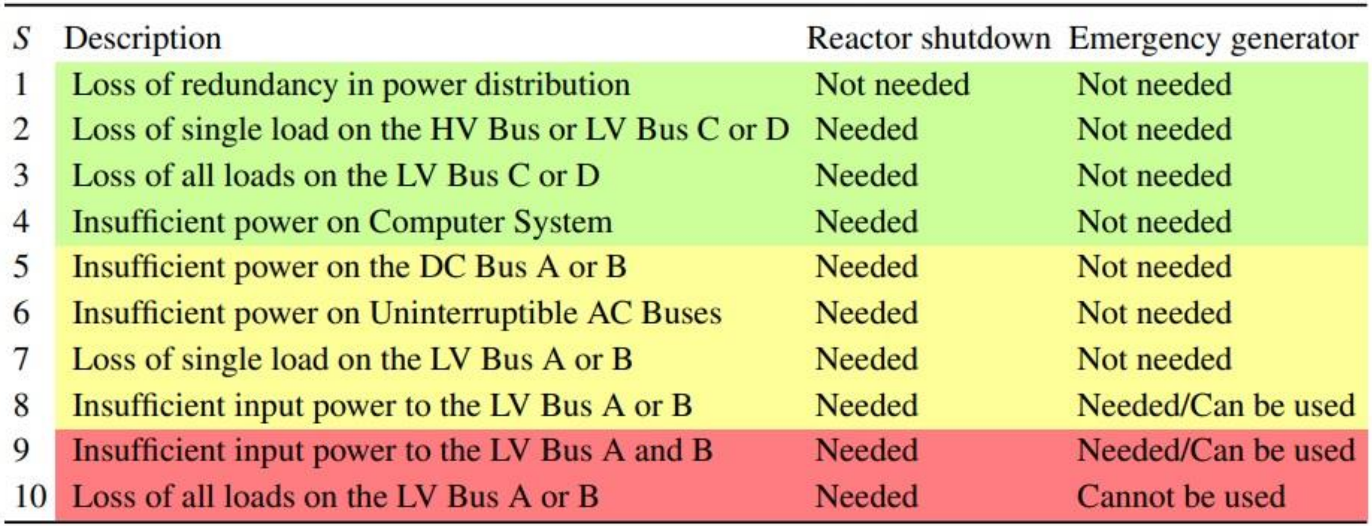


Fig. 1 Standard configuration of the HTTR EF with three modifications (marked by red line) considered in terms of system reliability improvement

Extended FMEA methodology for HTGR

- FMEA of HTTR electrical system (Severity)

Table 1. rating scale for severity (*S*)



S	Description	Reactor shutdown	Emergency generator
1	Loss of redundancy in power distribution	Not needed	Not needed
2	Loss of single load on the HV Bus or LV Bus C or D	Needed	Not needed
3	Loss of all loads on the LV Bus C or D	Needed	Not needed
4	Insufficient power on Computer System	Needed	Not needed
5	Insufficient power on the DC Bus A or B	Needed	Not needed
6	Insufficient power on Uninterruptible AC Buses	Needed	Not needed
7	Loss of single load on the LV Bus A or B	Needed	Not needed
8	Insufficient input power to the LV Bus A or B	Needed	Needed/Can be used
9	Insufficient input power to the LV Bus A and B	Needed	Needed/Can be used
10	Loss of all loads on the LV Bus A or B	Needed	Cannot be used

Extended FMEA methodology for HTGR

- FMEA of HTTR electrical system (Occurrence)

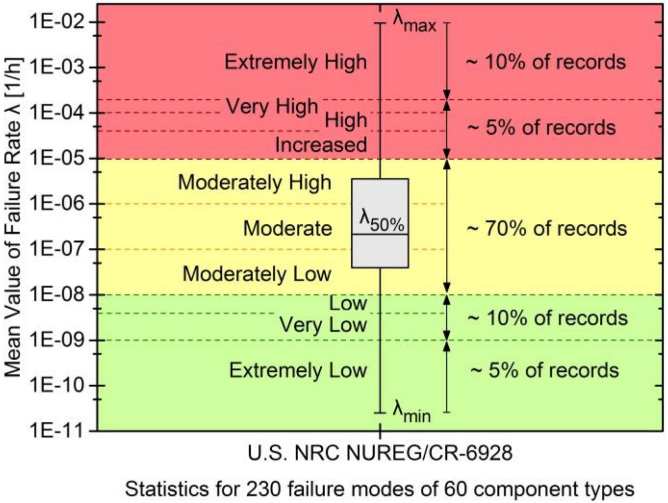
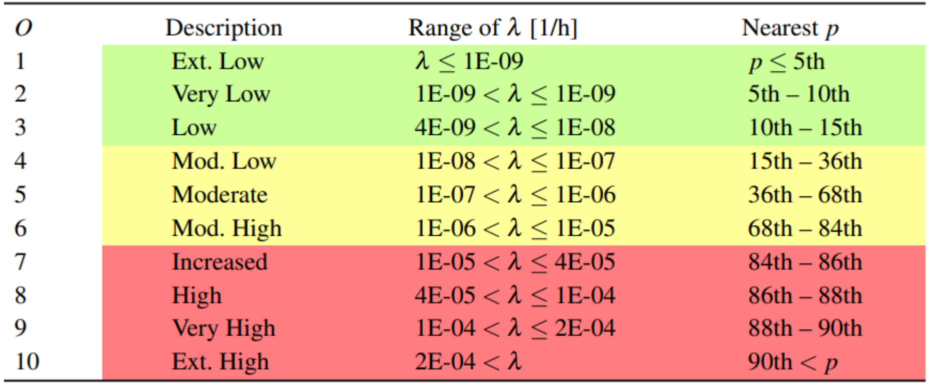


Fig. 2 Distribution of the failure rate values for a variety of component types and failure modes as collected in the U.S. NRC NUREG/CR-6928

Table 2. FMEA rating scale for Occurrence (p – the nearest percentile of the U.S. NRC data distribution corresponding to the boundary value of failure rate

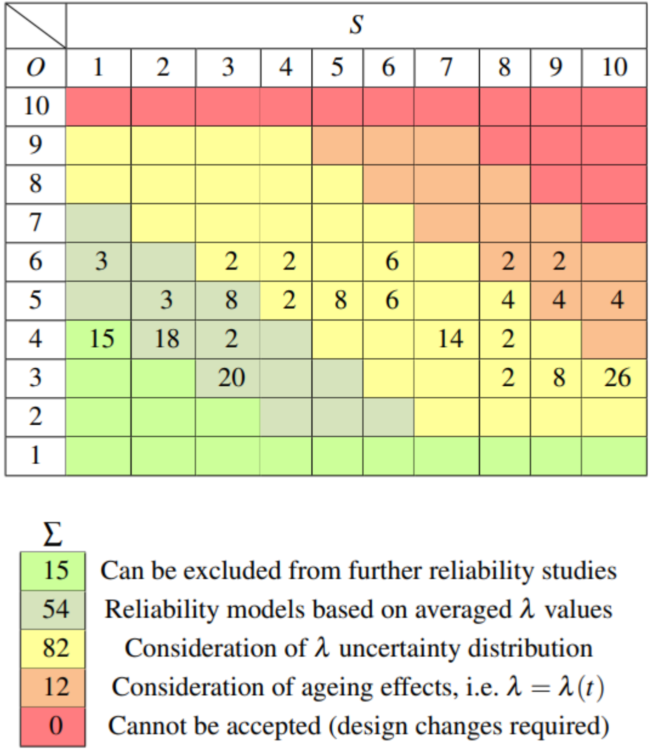


O	Description	Range of λ [1/h]	Nearest p
1	Ext. Low	$\lambda \leq$ 1E-09	$p \leq$ 5th
2	Very Low	1E-09 $< \lambda \leq$ 1E-09	5th – 10th
3	Low	4E-09 $< \lambda \leq$ 1E-08	10th – 15th
4	Mod. Low	1E-08 $< \lambda \leq$ 1E-07	15th – 36th
5	Moderate	1E-07 $< \lambda \leq$ 1E-06	36th – 68th
6	Mod. High	1E-06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

Extended FMEA methodology for HTGR

- **Gradual screening approach**

Table 3. Risk matrix of the HTTR EF (the cells include the number of identified failures)



	S									
O	1	2	3	4	5	6	7	8	9	10
10										
9										
8										
7										
6	3		2	2		6		2	2	
5		3	8	2	8	6		4	4	4
4	15	18	2				14	2		
3			20					2	8	26
2										
1										

Σ	
15	Can be excluded from further reliability studies
54	Reliability models based on averaged λ values
82	Consideration of λ uncertainty distribution
12	Consideration of ageing effects, i.e. $\lambda = \lambda(t)$
0	Cannot be accepted (design changes required)

Extended FMEA methodology for HTGR

- Failure rate uncertainties

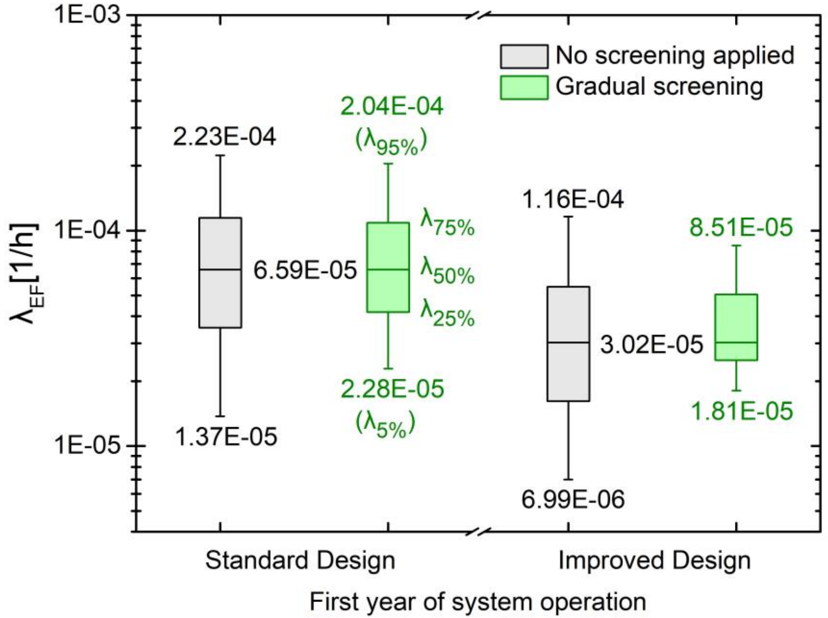


Fig. 3 Failure rate of the HTTR electrical facility (λ_{EF}) during the first year of the system operation

- Ageing phenomena modeling

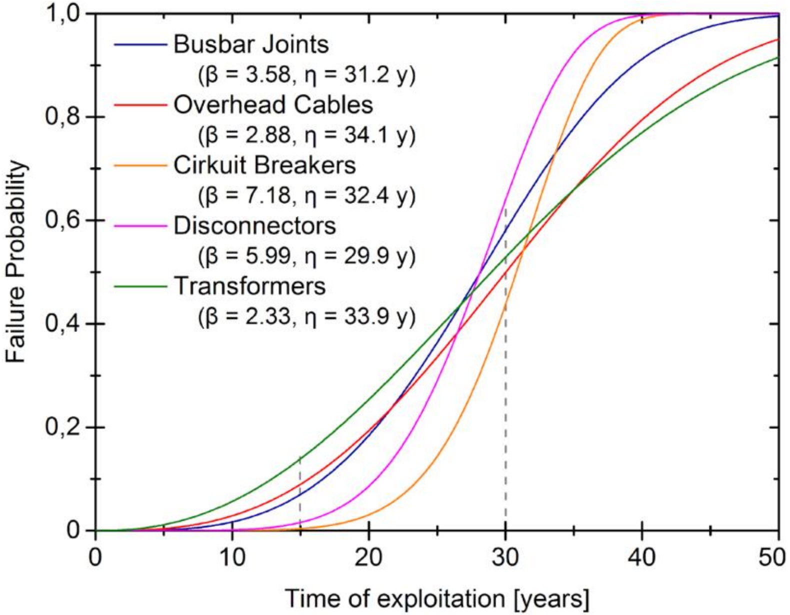


Fig. 4 Cumulative failure probability of the selected electrical components

Extended FMEA methodology for HTGR

- Time-dependence failure rates

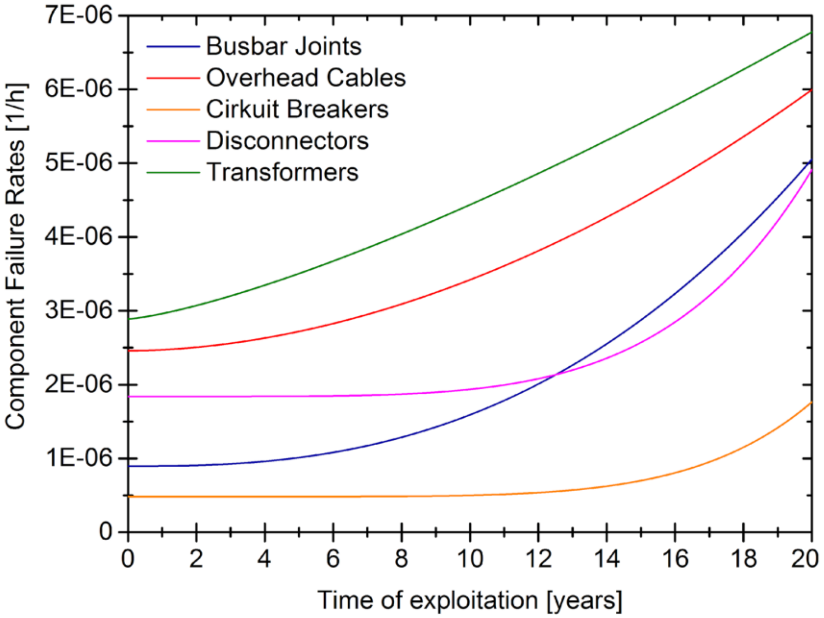


Fig. 5 Time-dependent failure rate of the HTTR electrical facility (λ_{EF})

- Probability density of the component failure rates

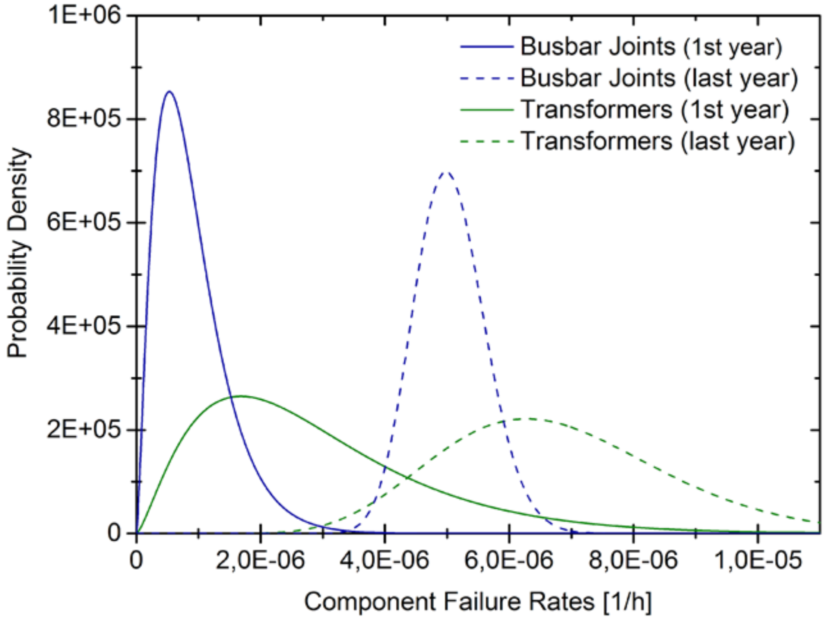


Fig. 6. Probability density of the component failure rates for the first and last year of operation

Extended FMEA methodology for HTGR

- The n-th-order bounds of the system failure rate (λ_{EF}) for the first and last year of the system operation

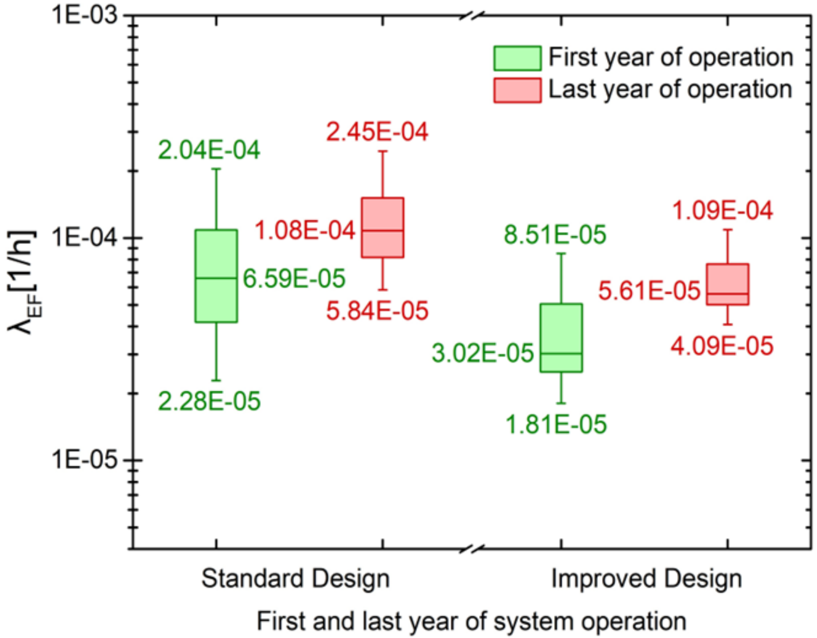


Fig. 7. Failure rate of the electrical facility (λ_{EF}) for the first year of the system operation

Vessel Cooling System (VCS)

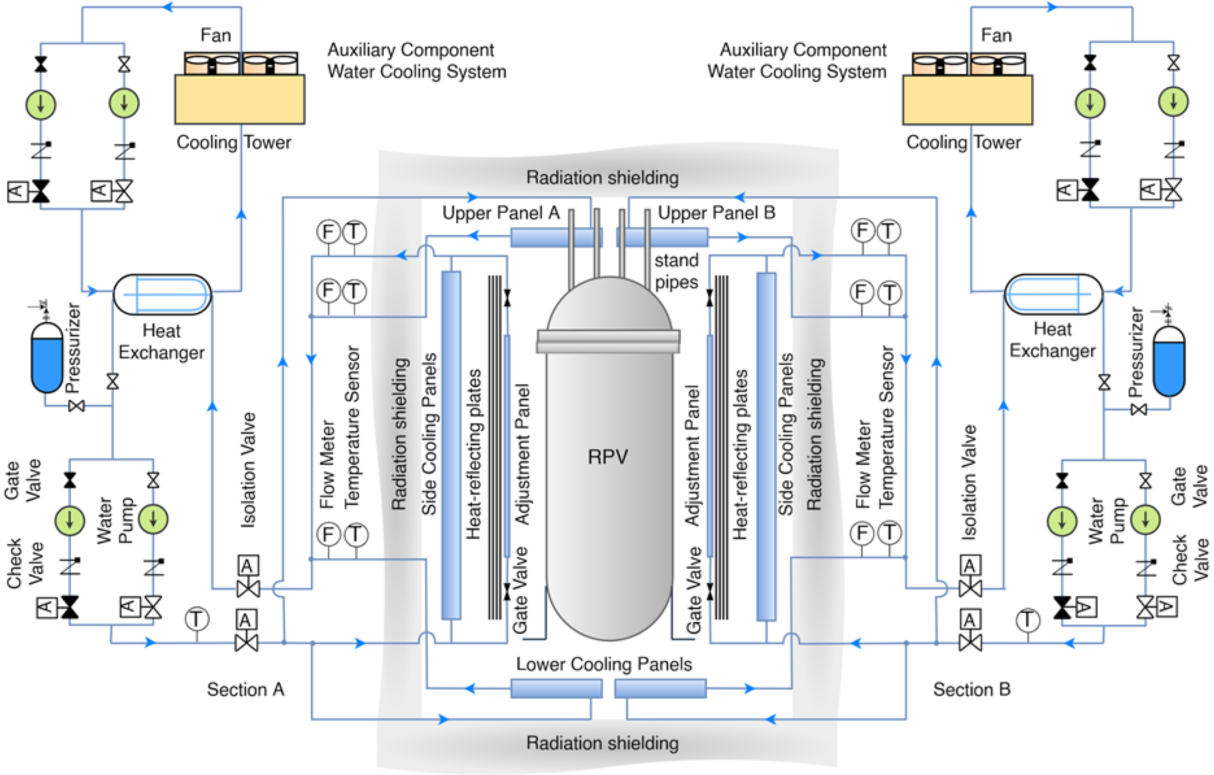


Fig. 8. Schematic diagram of the HTTR Vessel Cooling System

Reliability and availability simulations

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

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

Where, t is operating time, β is a shape parameter, and η is a scale parameter

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

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

Where, $SH_{VCS(1/2)}$ denotes the sum of all service hours of the VCS system assuming at least one of two sections operated at 100% flow rate and $CM_{VCS(1/2)}$ is the total number of hours spent for corrective maintenance of VCS over the whole life cycle to restore its minimal operability after failures.

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

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

RBD structure of VCS

- Parallel-unit operation mode (Model 1) :

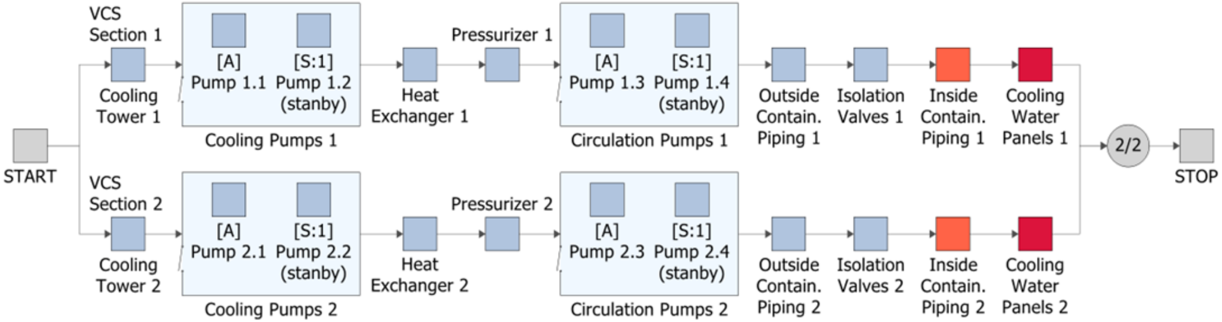


Fig.9. Reliability Block Diagram corresponding to the parallel-unit operation mode of the VCS system

- Single-unit operation mode (Model 2):

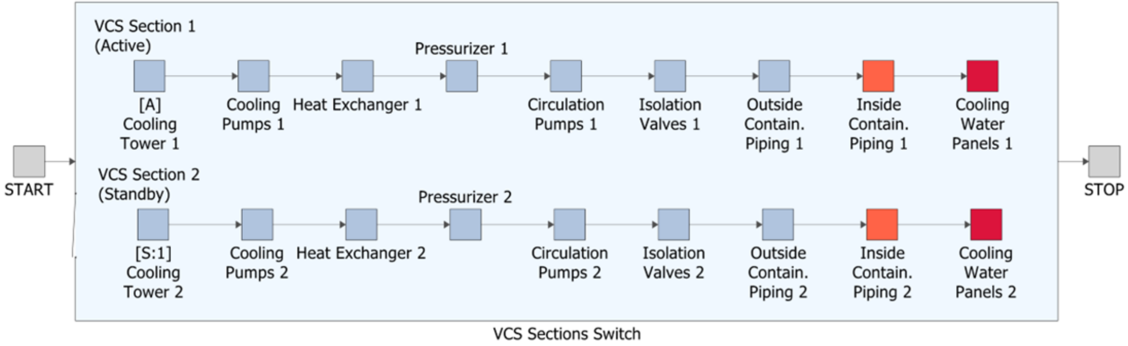


Fig.10. Reliability Block Diagram corresponding to the parallel-unit operation mode of the VCS system

Life-cycle reliability and availability simulation of VCS (model 1)

- Under normal operation

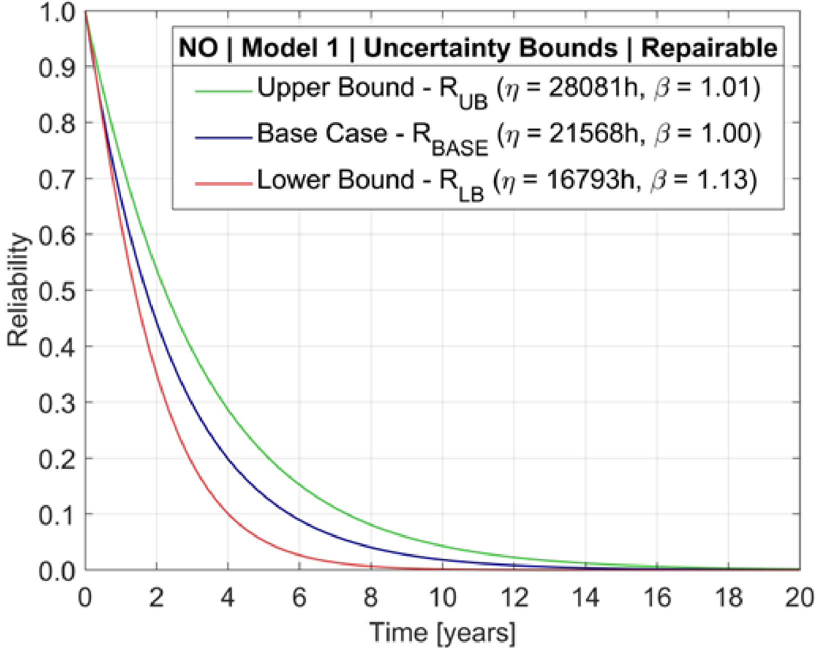


Fig. 10. Life-cycle reliability of the VCS system determined for the parallel-unit mode (Model 1) under normal operation

- Under accident condition

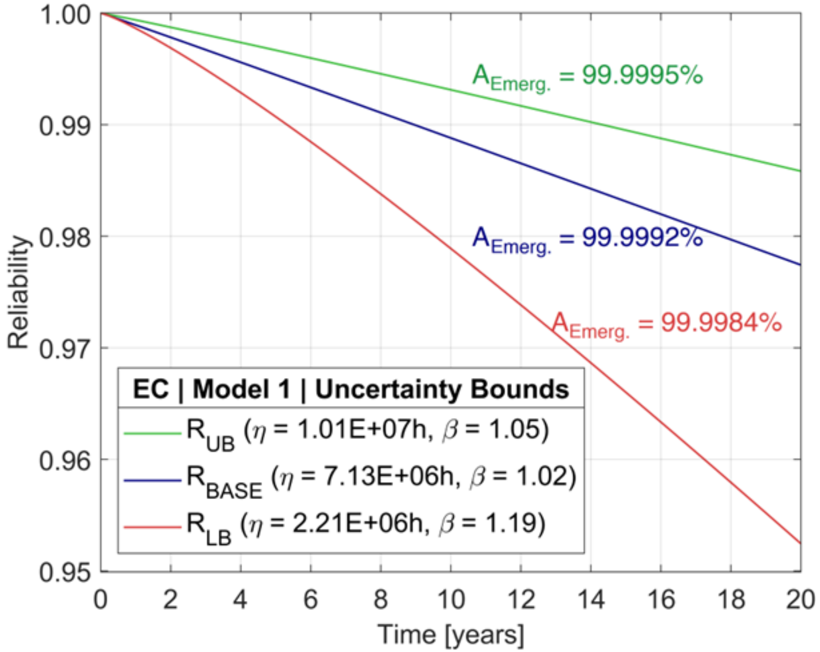


Fig. 11. Life-cycle reliability of the VCS system determined for the parallel-unit mode (Model 1) corresponding to the emergency conditions (one of two VCS sections is required)

Life-cycle reliability and availability simulation of VCS (model 2)

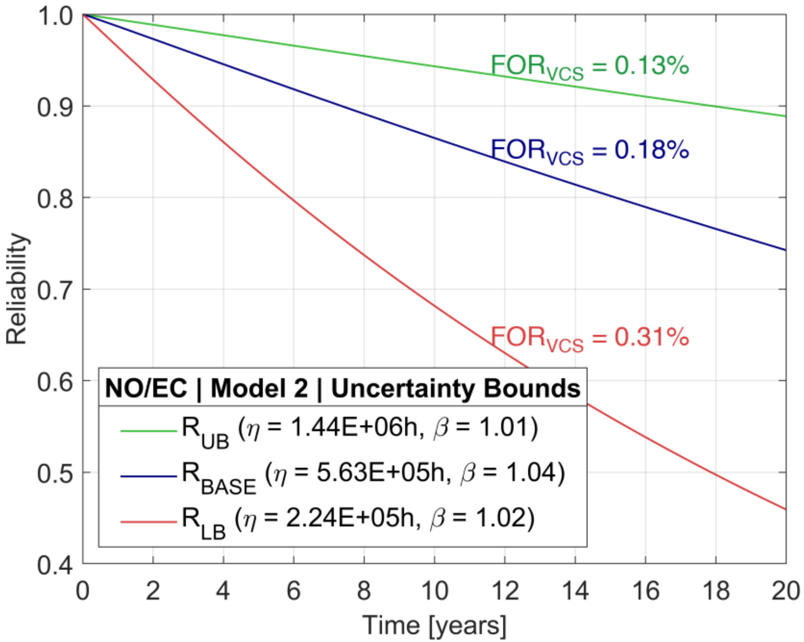
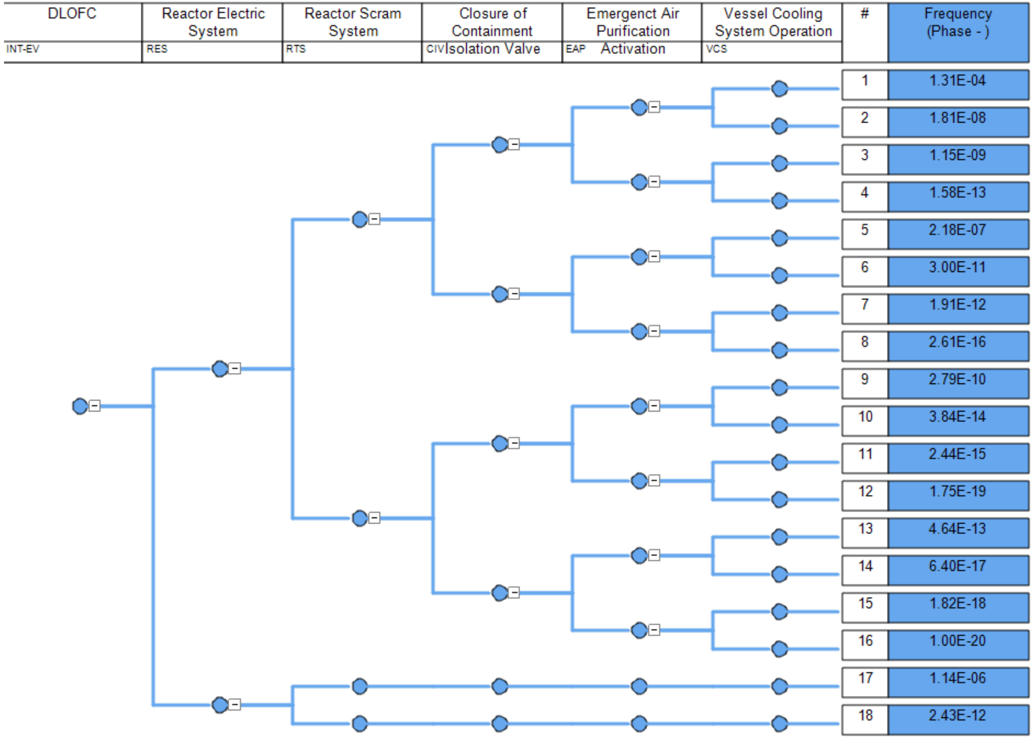


Fig. 12. Life-cycle reliability of the VCS system determined for the single-unit mode (Model 2) under normal operation.

Event tree of DLOFC accident

$$P(\text{sequence i}) = P(\text{initiating event}) \prod_{j=1}^{n} P(\text{top event j})$$

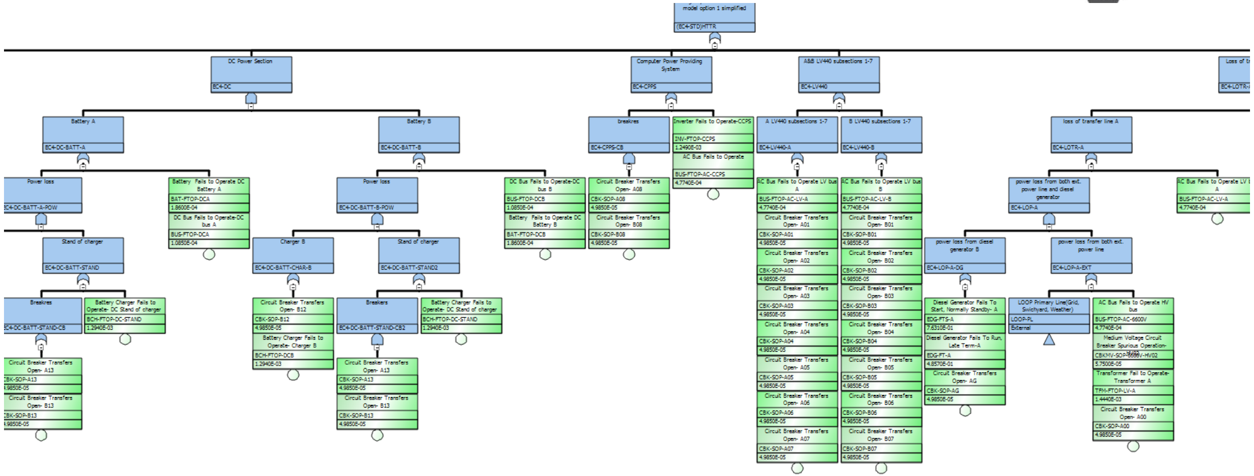


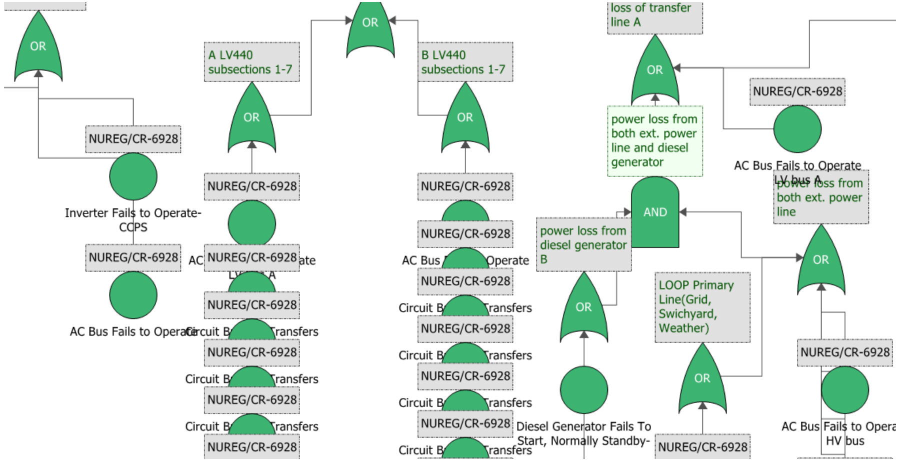
#	Frequency (Phase -)
1	1.31E-04
2	1.81E-08
3	1.15E-09
4	1.58E-13
5	2.18E-07
6	3.00E-11
7	1.91E-12
8	2.61E-16
9	2.79E-10
10	3.84E-14
11	2.44E-15
12	1.75E-19
13	4.64E-13
14	6.40E-17
15	1.82E-18
16	1.00E-20
17	1.14E-06
18	2.43E-12

Fig. 13. Event tree for the initiating event DLOFC

Conventional and simulation-based fault tree analysis of DLOFC accident

$$P(\text{top event}) = 1 - \prod_{i=1}^{n}(1-P_i)$$





$$R_S = \prod_{i=1}^{n} R_i$$

$$R_S = 1 - \prod_{i=1}^{n}(1-R_i)$$

$$R_s(k,n,R) = \sum_{r=k}^{n}\binom{n}{r}R^r(1-R)^{n-r}$$

$$R_s(k,n,R_1,R_2,\ldots,R_n) = \sum_{r=k}^{n}\binom{n}{r}\prod_{i=1}^{r}R_i\prod_{j=r+1}^{n}(1-R_j)$$

Improved approach to probability estimation in event tree analysis

- Failure probability of a set of n safety systems involved in a specific event sequence during DLOFC accident

$$\lambda_{Seq.}^{DLOFC} = \lambda^{DLOFC} \prod_{i=1}^{n} \left(1 - R_{Sys\_NonRepair,i}(T_{DLOFC})\right)$$

- Extension of simulation-based improvement using conditional probability

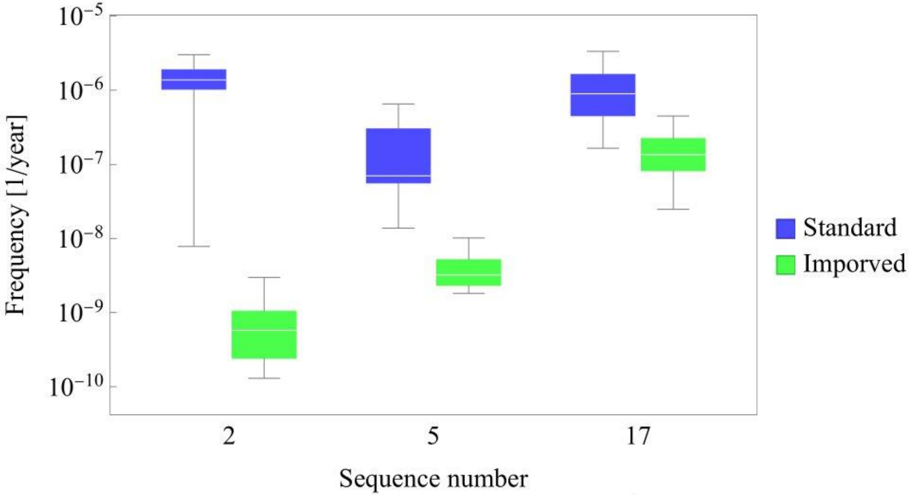
$$\lambda_{Seq.}^{DLOFC} = \lambda^{DLOFC} \prod_{i=1}^{n} \left(1 - R_{Sys\_NonRepair,i}(T_{DLOFC} | T)\right)$$

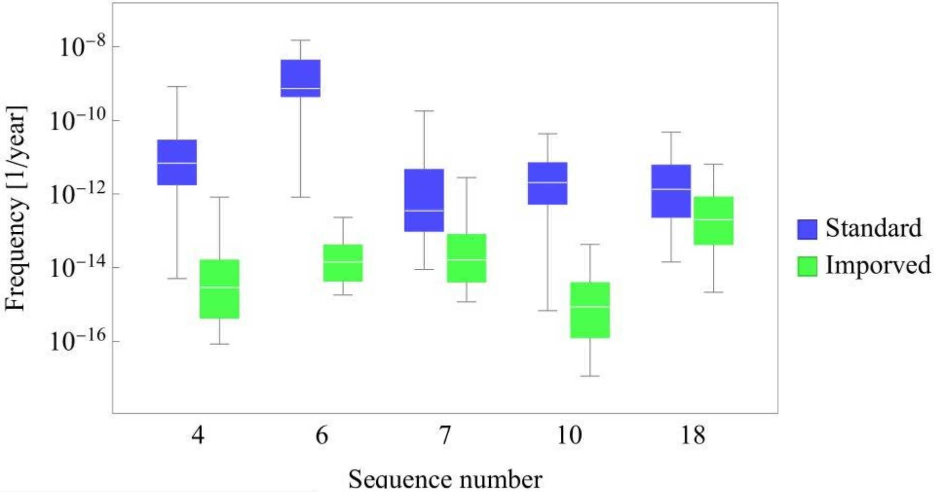
- Possibility of repairing and performing preventive maintenance on the associated safety systems after any failure

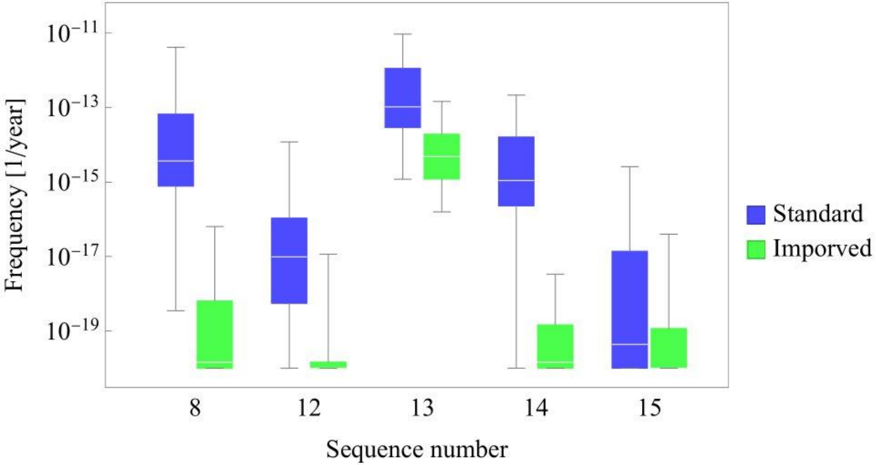
$$\lambda_{Seq.}^{DLOFC} = \lambda^{DLOFC} \prod_{i=1}^{n} \left(1 - \left(A_{\mathrm{Emrg.},i} \cdot R_{Sys\_Repair,i}(T_{DLOFC} | T)\right)\right)$$

Where $R_{Sys\_NonRepair}(T_{DLOFC}|T)$ the probability that a component or system will continue to operate without failure for a specific mission time, denoted as T_{DLOFC}, given that it has already been in operation and survived up to a certain time T.

Improved approach to probability estimation in event tree analysis







Summary and overall conclusions

- The applicability of conventional PSA method developed for LWRs raises concerns regarding their ability to accurately capture the operational characteristics of HTGRs.
- Therefore, the primary objective of my thesis was to improve the traditional PSA methodologies and address their limitations when applied to HTGRs, in order to provide a more comprehensive and accurate assessment.
- To this end, a novel approach based on life-cycle simulations of system reliability and availability was proposed using event tree technique and fault tree analysis.
- Subsequently, the standard fault tree analyses were replaced with a simulation-based method to provide a more accurate representation of event sequences probability.
- My research findings indicate that **the standard PSA approach leads to pessimistic results for HTGRs, while the improved approach resulting in reducing and more accurate frequencies of the sequences.**
- The results provide valuable insights for informed risk decision-making, facilitating effective risk assessment and mitigation strategies.

Publications

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Failure mode and reliability study for Electrical Facility of th
High Temperature Engineering Test Reactor

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ARTICLE INFO

Keywords:
HTTR reactor
Electrical Facility
FMEA-based Gradual Screening
Nuc-Chem facility
Reliability

ABSTRACT

The first-of-a-kind commercial electricity and hydrogen
Atomic Energy Agency (JAEA) to establish the industri
Reactors (HTGR). The High Temperature Engineering Te
test cogeneration plant to demonstrate its safety features
The aim of this work was to assess the frequency of the un
the HTTR Electrical Facility. The system analysis has bee
Analysis (FMEA). The new FMEA-based Gradual Screenin
to select the most relevant failure modes. The initial cal
the system indicated that the reliability may be insufficie
for about 20 years. Therefore, several modifications of the
enhancement. However, the updated results are still belo
of research in reliability engineering and creates a challen
of the joint nuclear-chemical facilities.

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Failure modes analysis of the electrical power supply for the
ature Gas-cooled Reactor

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High Temperature Gas-cooled Reactor (HTGR) is a Generation IV nuclear techn
for heat and power cogeneration. The GEMINI+ is an HTGR-based plant design
of the foreseen cogeneration facilities. The reliability of such complex nucle
challenge worth discussing. Here, we present a systematic approach for the ide
causing undesired interruptions of the GEMINI+ operation. Failure Mode and
with FMEA-based Gradual Screening methods are applied to classify the elect
priority. Different strategies for modeling the components' reliability are propos
presenting a unified approach to the reliability studies for electrical systems of th

Keywords: FMEA, HTGR Reactors, HTGR-based Cogeneration, GEMINI+, Pl

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Reliability and availability simulation for vessel cooling system of the high temperature engineering test reactor

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ARTICLE INFO

Keywords:
Vessel Cooling System
Reliability
Availability
Electricity-hydrogen cogeneration
Reactor cavity cooling system

ABSTRACT

The article deals with the problem of risk analysis for new and unique nuclear facilities where safety-relat
systems are continuously operated during normal exploitation. A non-standard approach to system modeli
was applied which goes beyond traditional method suitable for on-demand safety systems with a fixed missi
time. As an example, the Vessel Cooling System (VCS) of the Japanese High Temperature Engineering Te
Reactor (HTTR) has been analyzed in terms of life-cycle reliability and availability. Normal operation a
emergency conditions have been considered, differing in the requirements for the system performance. In t
former, the VCS reliability for cooling the biological shield around the Reactor Pressure Vessel (RPV) has be
examined. In the latter, the VCS availability to remove the residual heat from the reactor core and RPV has be
simulated. The results are of high importance for the safety and profitability of the HTTR-based electricit
hydrogen cogeneration plant (HTTR-GT/H2). The high reliability of the VCS under emergency conditions h
been confirmed, thus contributing to the probabilistic safety assessment (PSA). Moreover, the fraction of t
Forced Outage Rate (FOR) caused by VCS failures has been determined, thus contributing to the plant prof
ability studies.

Thank you for your time and attention

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