Simulation based analysis of lifetime reliability and availability for Electrical Systems in High Temperature Gas Reactors

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Grzegorz Mrugała

Division of Nuclear Energy and Environmental Studies

Fundusze Europejskie Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska Europejski Fundusz Społeczny

Introduction

The overall goals of this work:

- Determine the lifetime reliability and availability for the HTGR, HTTR and GEMINI+ electrical system in Normal Operation and Emergency Conditions.
- Comparison of alternative models and different design options in terms of the ability to provide power supply to electrical loads
- Determination of Forced Outage Rate of each electrical system design and identification of the individual components on this result
- Proposing changes to the project of HTGR electrical system to improve reliability and availability parameters

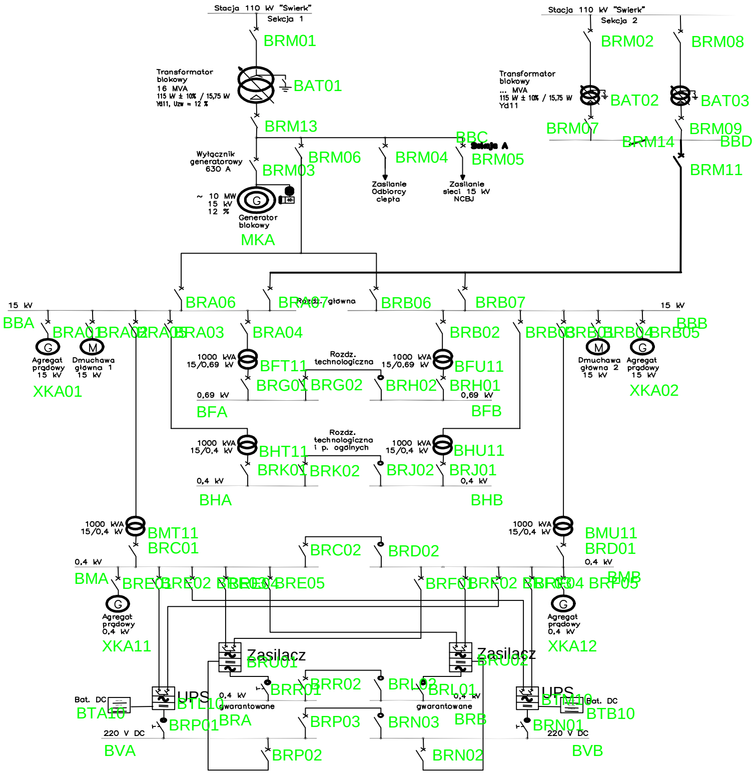
Reliability study of electrical systems in Nuclear Facilities

- Karol Kowal.”Lifetime reliability and availability simulation for the electrical system of HTTR coupled to the electricity-hydrogen cogeneration plant”, Reliability Engineering and system safety,

DOI: 10.1016/j.ress.2022.108468

- Karol Kowal, Mina Torabi,. “Failure modes analysis of the electrical power supply for the GEMINI+ High Temperature Gas-cooled Reactor”, DOI: 10.3850/978-981-18-5183-4_R18-18-464-cd

HTGR Electrical System Diagram



HTGR Electrical System Diagram (Technical description of the research HTGR. Z3-1 version 2.2)

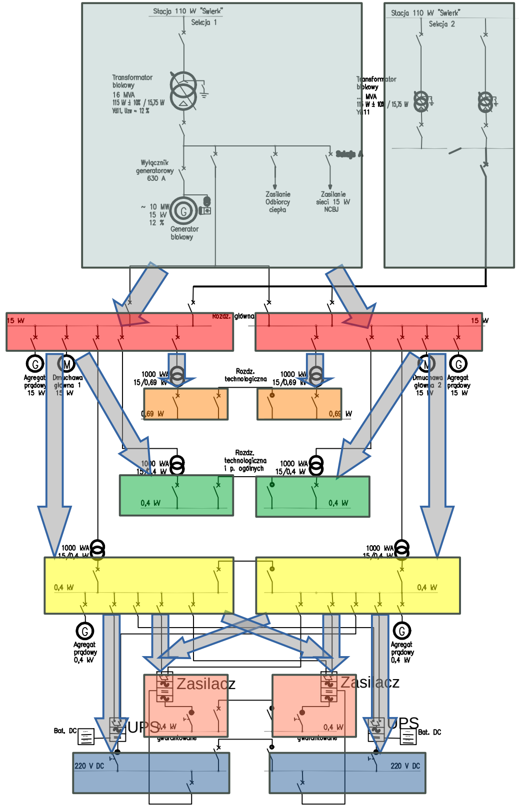
HTGR Electrical System Diagram

External Power Lines

MV Power Section

LV 0,69 kV GPB

LV 0,4 kV GPB



LV 0,4 kV EPB

DC section

LV Unitteruptible Power System

HTGR Electrical System Diagram

Electrical systems for each nuclear facility

Component number of each system of electrical power distribution designs

	HTTR		GEMINI		HTGR		HTGR improved	
	systems	comp. no.	systems	comp. no.	systems	comp. no.	systems	comp. no.
Offsite power line	1	2	3	12	3	23	3	23
MV Power Section	1	8	1	5	2	12	2	10
LV general purpose power section (large drivers)	0	0	1	3	2	8	1	3
LV general purpose power section (other loads)	2	24	2	8	2	8	2	10
LV emergency power sections	2	34	2	14	2	18	2	14
Emergency diesel generators	2	2	2	2	4	4	4	4
DC power section	2	9	2	16	2	12	2	12
LV Unitteruptible Power System	3	8	5	30	2	8	2	10
Total component number		**87**		**90**		**93**		**86**

System Components Data Set

HTGR system components Data Set

Component failure mo	Description	λ mean	λ 5%	λ 50%	λ 95%	Source
BAT-FTOP	Battery Fails to Operate	3,72E-07	2,55E-07	3,67E-07	5,06E-07	US NRC NUREG-6928
BCH-FTOP-DC	Battery Charger Fails to Operate	2,59E-06	2,67E-07	2,00E-06	6,93E-04	US NRC NUREG-6928
BUS-FTOP-AC	AC Bus Fails to Operate	9,55E-07	6,10E-08	6,81E-07	2,75E-06	US NRC NUREG-6928
BUS-FTOP-DC	DC Bus Fails to Operate	2,17E-07	8,51E-10	9,85E-08	8,31E-07	US NRC NUREG-6928
CBK-SOP	Circuit Breaker Transfers Open	9,97E-08	7,52E-08	9,89E-08	1,27E-07	US NRC NUREG-6928
CBKMV-SOP	Medium Voltage Circuit Breaker Spurious Operation	1,15E-07	2,80E-10	4,81E-08	4,53E-07	US NRC NUREG-6928
EDG-FTS	Diesel Generator Fails To Start, Normally Standby	2,88E-03	1,52E-03	2,78E-03	4,60E-03	IAEA-TECDOC-478
EDG-FTLR	Diesel Generator Fails To Load And Run, Early	3,72E-03	1,14E-03	3,37E-03	7,49E-03	IAEA-TECDOC-478
EDG-FTR	Diesel Generator Fails To Run, Late Term	1,52E-03	3,53E-04	1,33E-03	3,36E-03	IAEA-TECDOC-478
INV-FTOP	Inverter Fails to Operate	4,94E-06	6,33E-07	2,50E-06	6,47E-06	US NRC NUREG-6928
LOOP-GR	Loss of offsite power grid-related,	1,26E-06	1,26E-08	6,69E-07	4,50E-06	US NRC NUREG-6928
LOOP-SC	Loss of offsite power switchyard-centered	1,53E-06	1,05E-06	1,51E-06	2,09E-06	US NRC NUREG-6928
LOOP-WR	Loss of offsite power weather-related	6,84E-07	3,78E-07	6,63E-07	1,07E-06	US NRC NUREG-6928
TFM-FTOP	Transformer Fail to Operate	2,89E-06	6,33E-07	2,50E-06	6,47E-06	US NRC NUREG-6928
EGSRE-FTR	AC generator steam turbine driven fail to run	7,20E-07				IAEA-TECDOC-478
EGSRE-FTS	AC generator steam turbine driven fail to start	4,50E-07				IAEA-TECDOC-478
UEYFO	isolating diode assembly fail to function	3,70E-06	4,10E-07		6,80E-06	IAEA-TECDOC-478
BAT-SC	Battery Short Circut	1,36E-07	7,51E-08	1,12E-08	3,33E-07	IAEA-TECDOC-478
BCH-SC	Battery Charger Short Circut	1,06E-07	3,29E-09	6,80E-08	3,40E-07	IAEA-TECDOC-478
BUS-SC-AC	AC Bus Short Circut	8,14E-07	5,26E-09	1,24E-07	3,38E-06	IAEA-TECDOC-478
BUS-SC-DC	DC Bus Short Circut	1,14E-06	3,74E-08	4,08E-07	4,50E-06	IAEA-TECDOC-478
CBKMV-SC	Medium Voltage Circuit Breaker Short Circut	3,77E-07	9,99E-08	3,04E-07	8,95E-07	IAEA-TECDOC-478
CBK-SC	Circuit Breaker Short Circut	2,69E-08	9,50E-10	1,01E-08	1,03E-07	IAEA-TECDOC-478
INV-SC	Inverter Short Circut	3,40E-06	2,00E-07	2,41E-06	1,00E-05	IAEA-TECDOC-478
TFM-SC	Transformer Short Circut	4,32E-06	2,75E-07	1,29E-06	1,87E-05	IAEA-TECDOC-478
Component type	Repair time		λ 5%		λ 95%	Source
Battery			5		100	IAEA-TECDOC-478
Battery Charger			5		10	IAEA-TECDOC-478
Power Bus			8		37	IAEA-TECDOC-478
Cable			5		15	IAEA-TECDOC-478
Circuit Breaker			6		219	IAEA-TECDOC-478
Inverter			26		200	IAEA-TECDOC-478
Offsite Power Line			1		14	IAEA-TECDOC-478
Transformer			5		370	IAEA-TECDOC-478

PSA initial conditions

- The predicted lifetime of facilities is foreseen for 20 years
- Duration of Outages for Preventive Maintenance and refueling is planed for 60 days per 2 years
- Reliability models consist only Failure To Operate and Short Circuit failure type events
- Coupling breakers was modeled by pair of circuit breakers

PSA Analysis

- Reliability

$$R_{exp.} = e^{-\lambda t}$$

- Availability

$$A_{cogen.} = \frac{SH}{SH + FOH_{ele.} + PMH}$$

$$A_{emerg.} = \frac{T_{up}}{T_{up} + T_{down}}$$

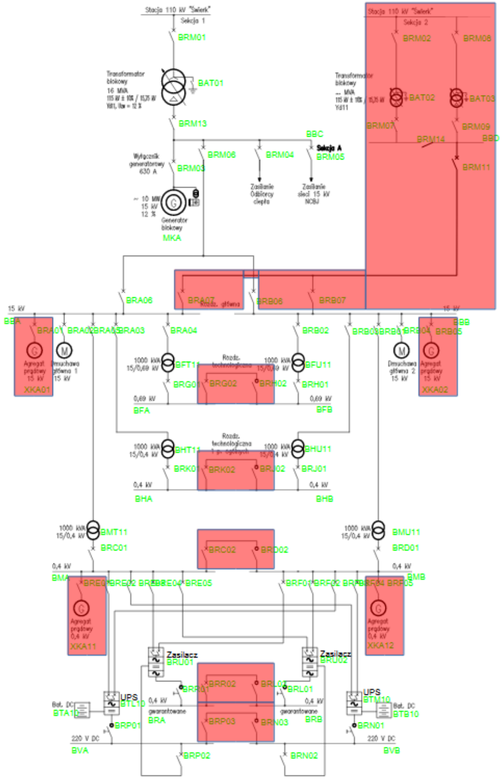
- Forced Outage Rate

$$FOR_{ele.} = \frac{FOH_{ele.}}{SH + FOH_{ele.}} \cdot 100\%$$

- λ- Failure rate [1/h]
- SH- Service Hours
- FOH_{ele}- Forced Outage Hours
- PMH- Preventive Maintenance Hours

- MTBF- Mean Time Between Failures
- MMTR- Mean Time To Repair
- FCI- Failure Criticality Index

HTGR Normal Operation



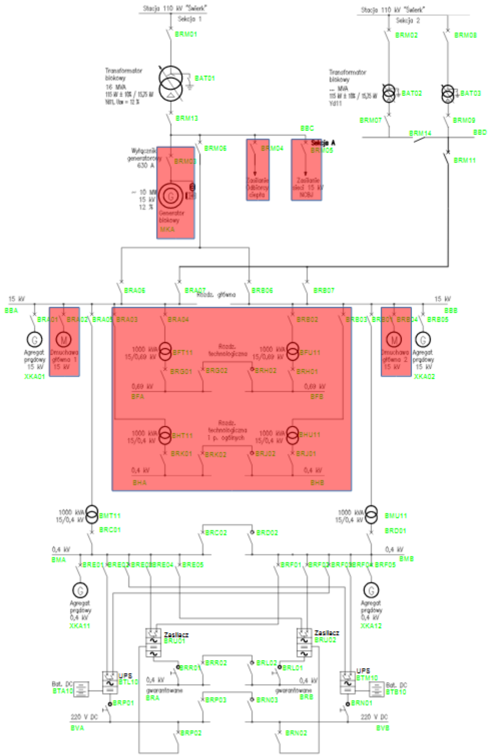
HTGR electrical system single-line diagram in Normal Operation

Normal Operation- insufficient power input to at least one of electrical loads is considered a system failure.

Since loss of basic power supply causes system failure auxiliary power supply are not considered such as:

- secondary external power line,
- emergency diesel generators,
- power bus switches,

HTGR Emergency Condition



HTGR electrical system single-line diagram in Emergency Conditions

Emergency Conditions- providing power to the safety-related loads that are: *Emergency Power Buses, DC Sections and Uninterruptible AC drivers.*

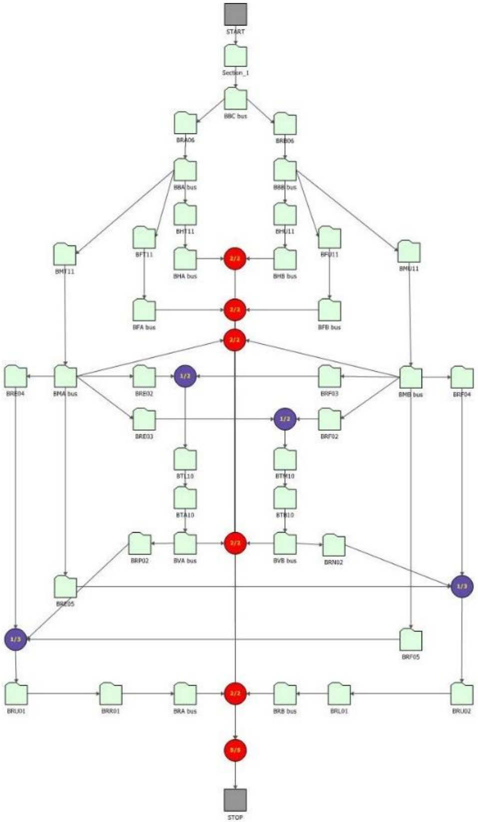
Secondary External Power Line, Emergency Diesel Generators and Power Bus Switches are now available.

Non safety related loads such as:

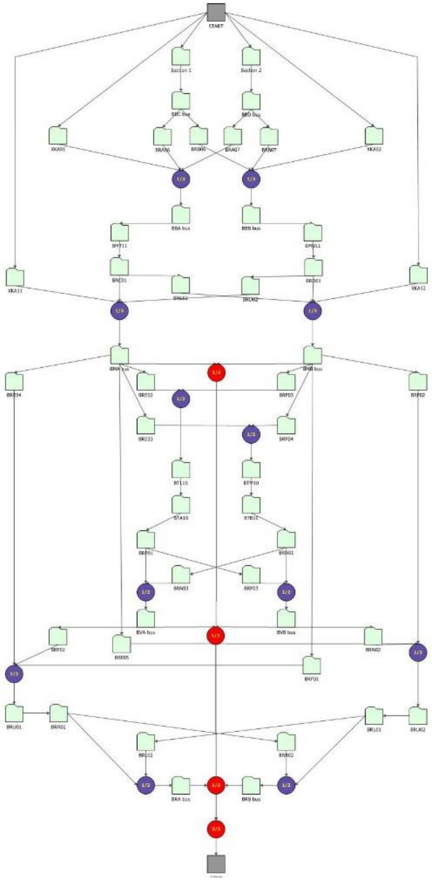
- AC generator
- External power Consumers
- Main Blowers
- General Purpose Buses

can be excluded from analysis as nonessential for the reactor shutdown and residual heat removal.

HTGR RBD models

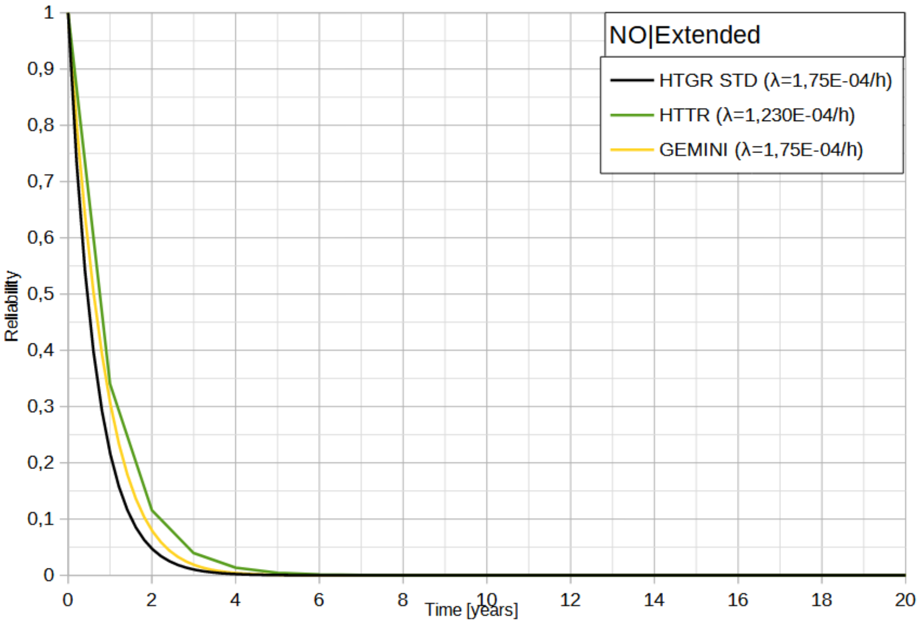


HTGR electrical system Normal Operation RBD model

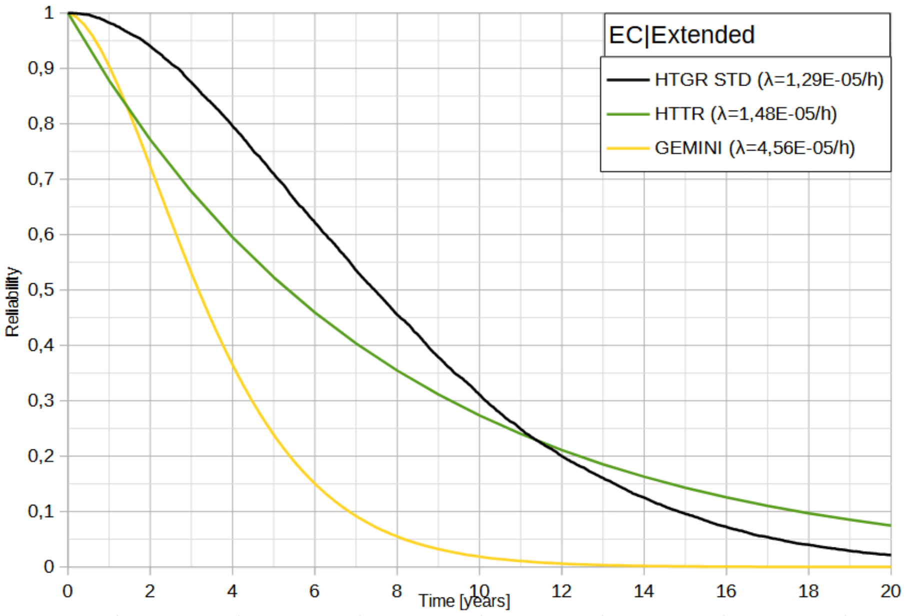


HTGR electrical system Emergency Condition RBD model

HTGR Reliability results

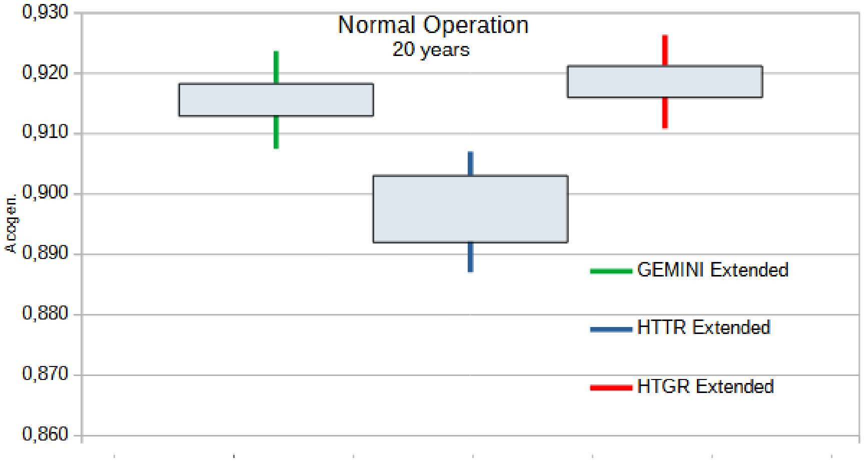


Lifetime Reliability of NPP electrical system Normal Operation

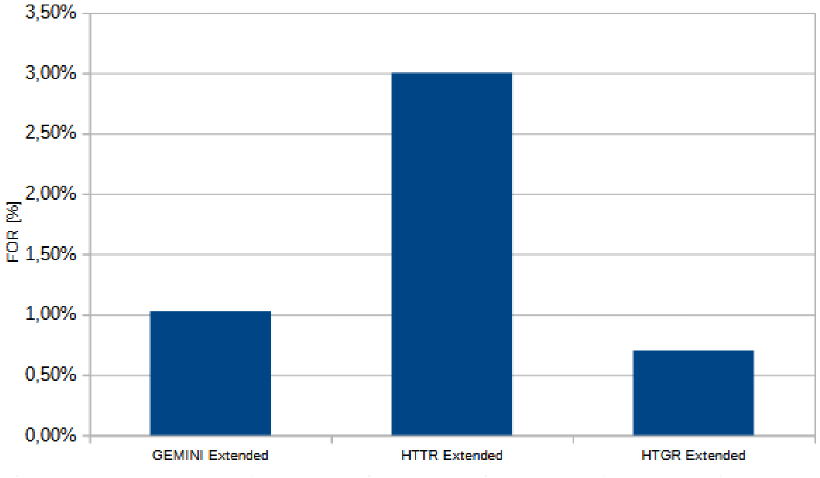


Lifetime Reliability of NPP electrical system Emergency Condition

HTGR Availability results

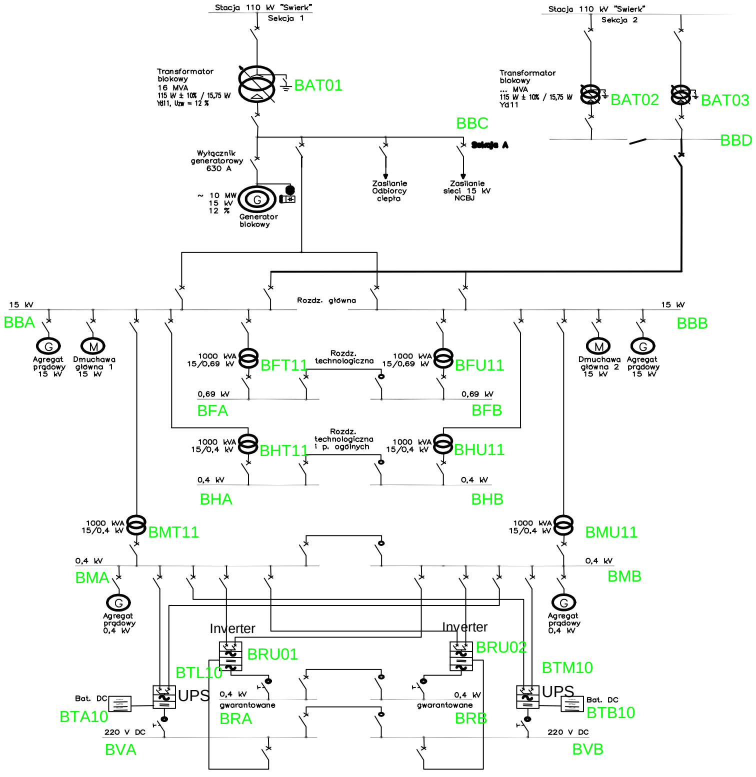


Availability for NPP cogeneration electrical system Normal Operation



Forced Outage Rate for NPP cogeneration electrical system Normal Operation

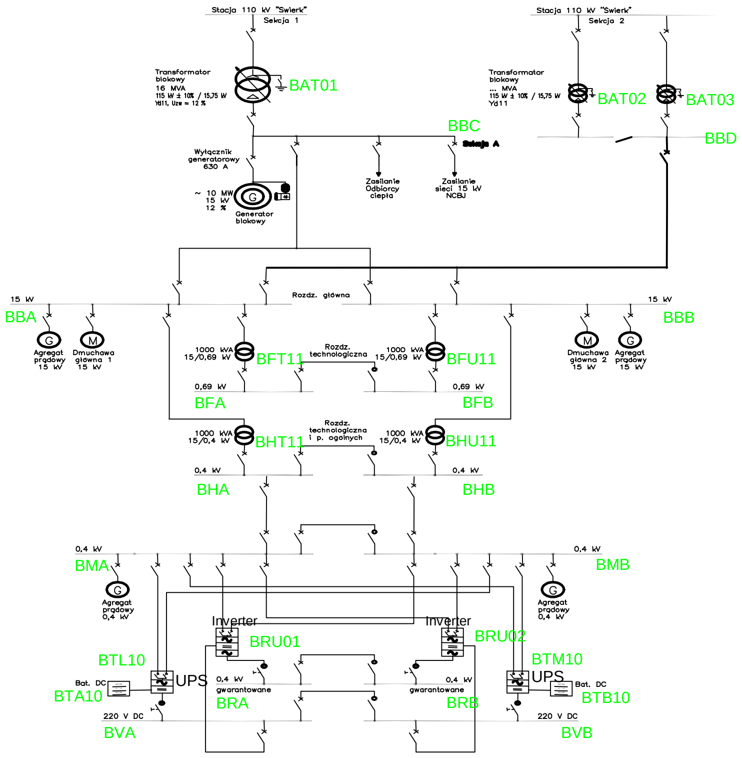
HTGR Electrical System Improved



HTGR Electrical System Standard

- Reduction of transformers BMT11 and BMU11. Supply of emergency power sections are now provided respectively through BHA and BHB power buses.
- Reduction of one of 0,69 kV sections as they are reserved for the largest power consumers which are not typically related to safety functions equipment thus their power supply redundancy is not required
- Replacement of BRU01 and BRU02 inverters to BRU03 and BRU04 chargers.

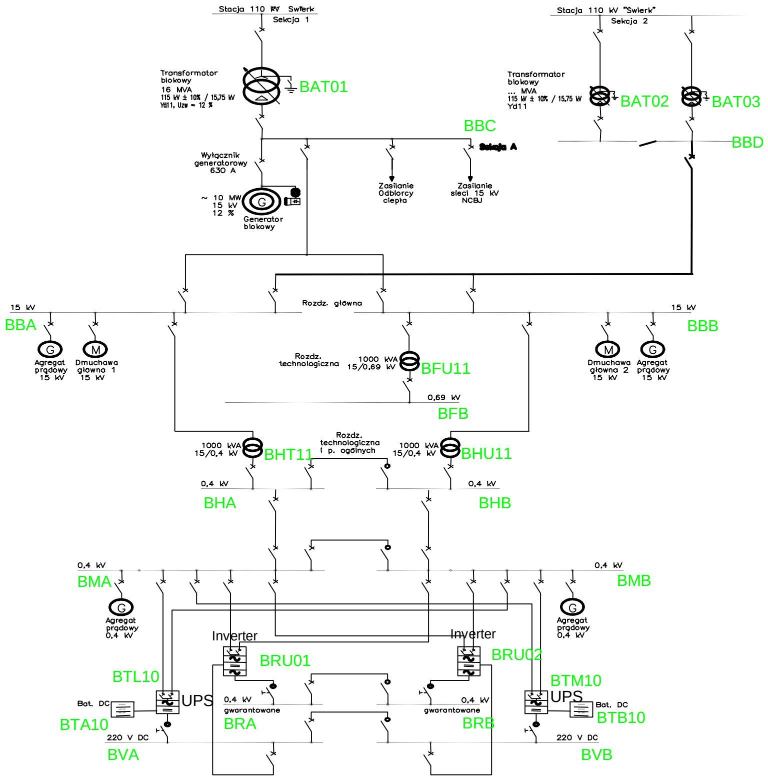
HTGR Electrical System Improved



HTGR Electrical System Improvment 1

- Reduction of transformers BMT11 and BMU11. Supply of emergency power sections are now provided respectively through BHA and BHB power buses.
- Reduction of one of 0,69 kV sections as they are reserved for the largest power consumers which are not typically related to safety functions equipment thus their power supply redundancy is not required
- Replacement of BRU01 and BRU02 inverters to BRU03 and BRU04 chargers.

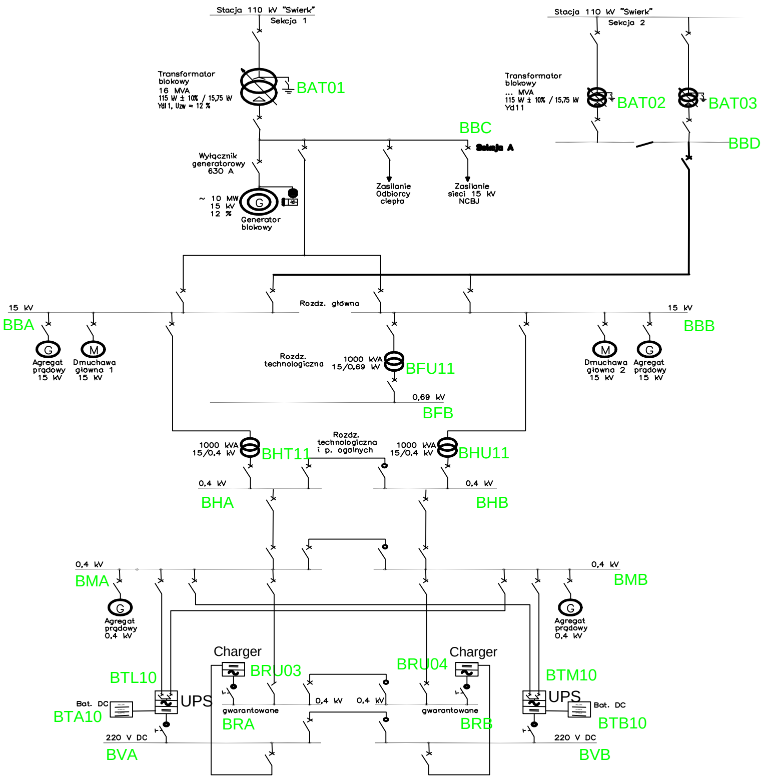
HTGR Electrical System Improved



HTGR Electrical System Improvment 1+2

- Reduction of transformers BMT11 and BMU11. Supply of emergency power sections are now provided respectively through BHA and BHB power buses.
- Reduction of one of 0,69 kV sections as they are reserved for the largest power consumers which are not typically related to safety functions equipment thus their power supply redundancy is not required
- Replacement of BRU01 and BRU02 inverters to BRU03 and BRU04 chargers.

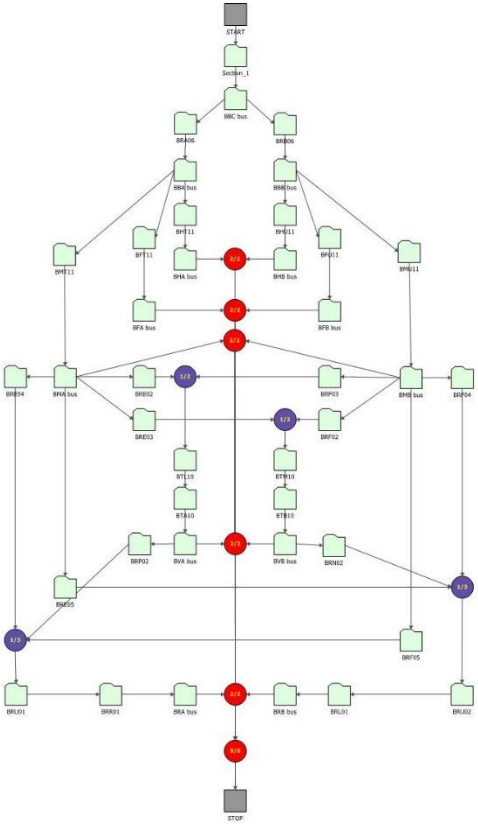
HTGR Electrical System Improved



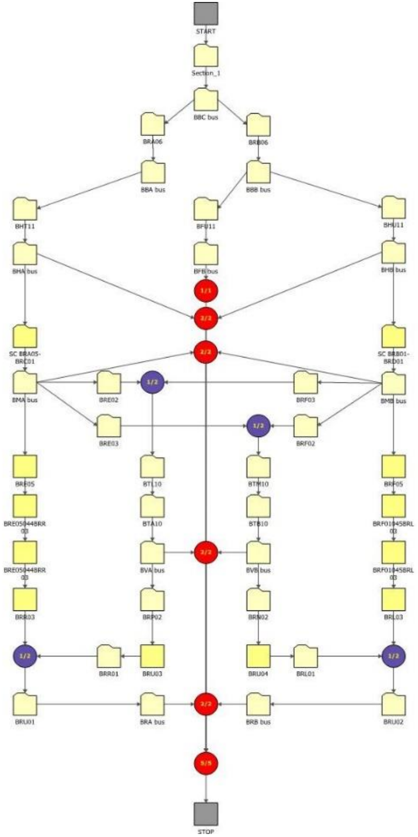
HTGR Electrical System Improvment 1+2+3

- Reduction of transformers BMT11 and BMU11. Supply of emergency power sections are now provided respectively through BHA and BHB power buses.
- Reduction of one of 0,69 kV sections as they are reserved for the largest power consumers which are not typically related to safety functions equipment thus their power supply redundancy is not required
- Replacement of BRU01 and BRU02 inverters to BRU03 and BRU04 chargers.

HTGR Improved RBD model

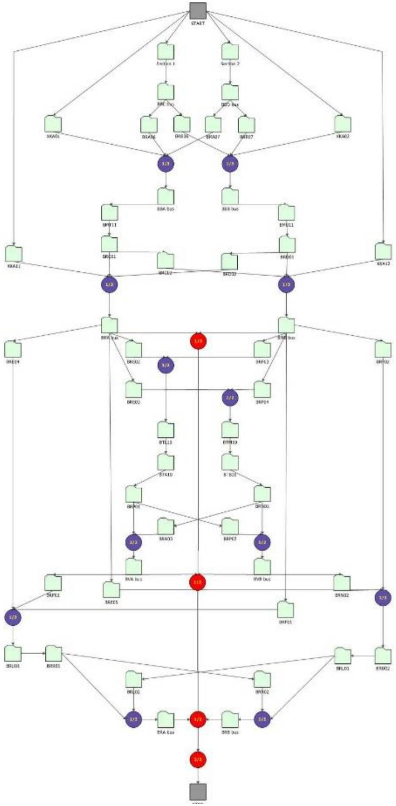


HTGR standard electrical system Normal Operation RBD model

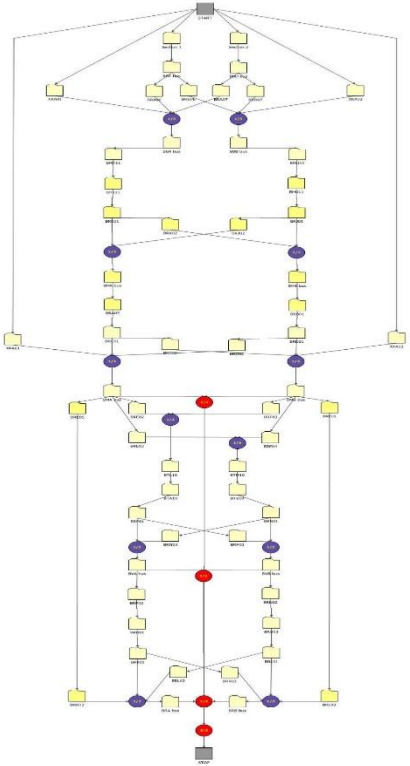


HTGR improved electrical system Normal Operation RBD model

HTGR Improved RBD model

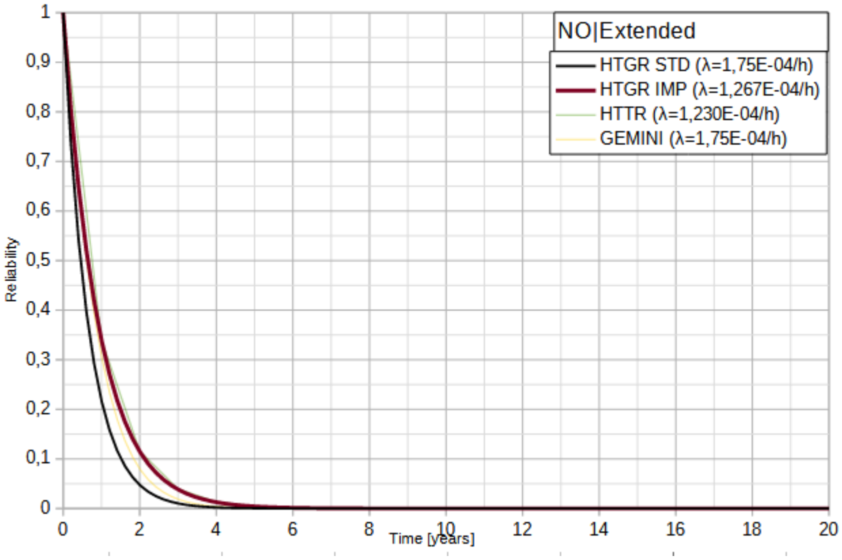


HTGR standard electrical system Normal Operation RBD model

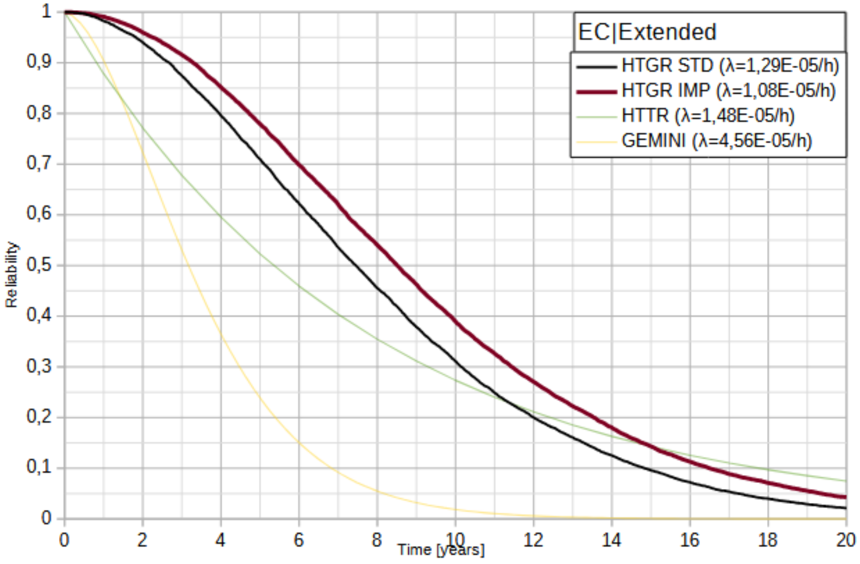


HTGR improved electrical system Normal Operation RBD model

HTGR Improved Reliability results

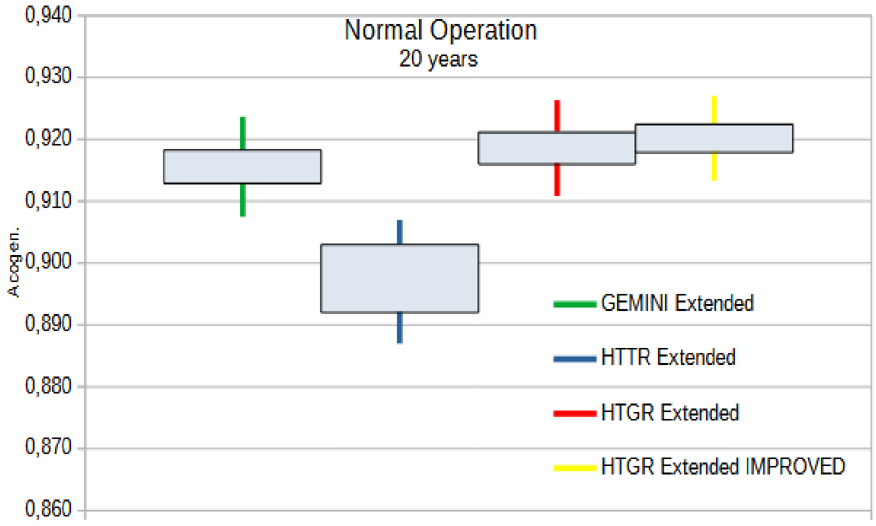


Lifetime Reliability of NPP electrical system Normal Operation

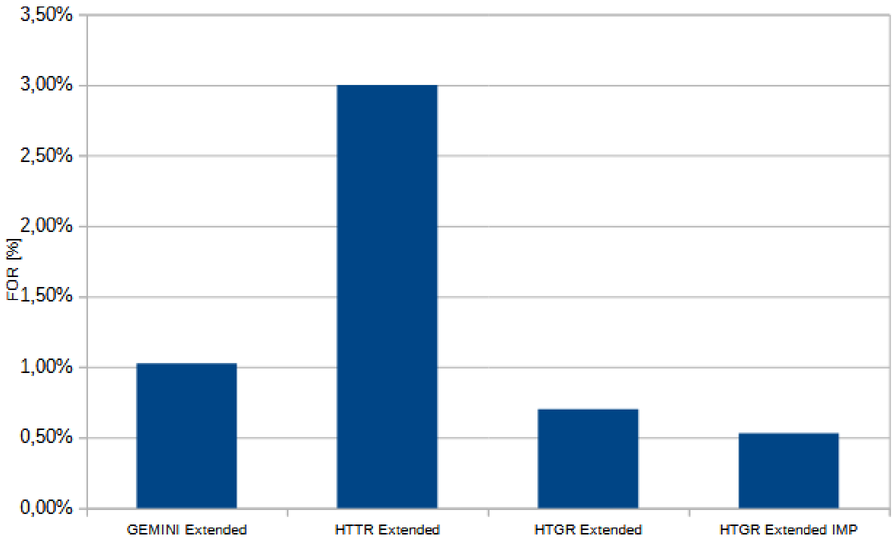


Lifetime Reliability of NPP electrical system Emergency Condition

HTGR Improved Availability results



Availability for NPP cogeneration electrical system Normal Operation

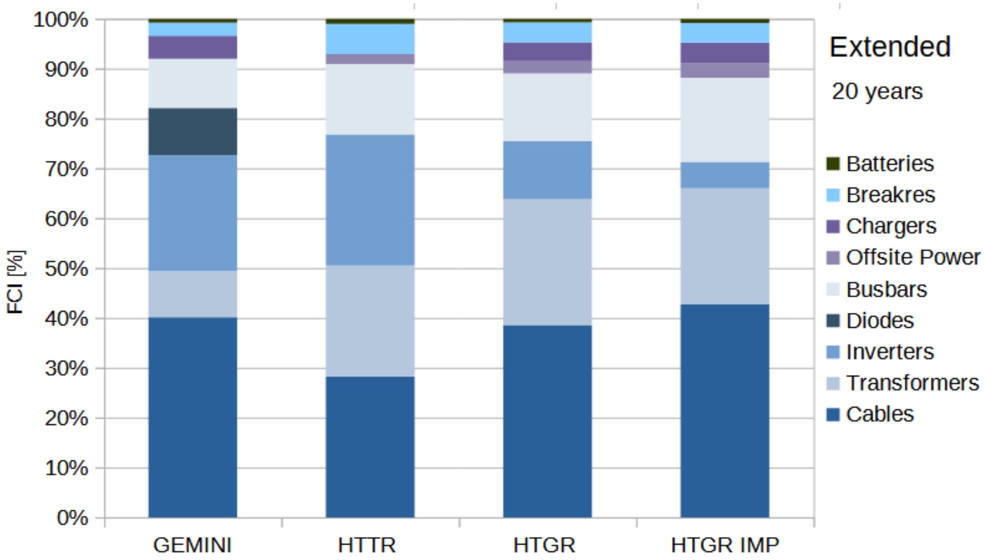


Forced Outage Rate for NPP cogeneration electrical system Normal Operation

HTGR Improved Availability results

System status	$A_{emerg.}$	MTBF [h]	MTTR [h]
HTTR EC Extended	0,9998	529465	87
GEMINI EC Extended	0,9999	3244444	12
HTGR EC Extended	0,9999	125142857	11
HTGR EC Extended Improved	0,9999	58400000	2

Availability for NPP electrical system under Emergency Condition and MTBF and MTTR in Normal Operation



Failure Criticality Index of electrical components in NPP Normal Operation

Concluding Remarks and Summary

- ✓ Presented results confirm high availability for the safety-related electrical loads during whole facility lifetime

- ✓ The results might be implemented for the future more advanced reliability study of the system.

- ✓ Reliability and availability are essential for HTGR based power plant to be competitive on commercial market

- ✓ Proposed system modification result in improved system are confirm only with adopted initial dataset.

- ✓ Optimization of the system can be also performed by improvement of component quality.

- ✓ The obtained HTGR availability results were compared with HTTR which is research reactor not orientated for long-term exploitation.

Thank you

for your attention

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

Grzegorz Mrugała

Division of Nuclear Energy and Environmental Studies

Grzegorz.Mrugala@ncbj.gov.pl

Fundusze Europejskie
Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska
Europejski Fundusz Społeczny