ANALYSIS OF RELIABILITY AND SAFETY OF INNOVATIVE GAS COOLED REACTORS

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Historical Development [2]:

GCR nuclear reactor - **Magnox**: - natural uranium as fuel,
- magnesium alloy as fuel clad,
- fuel element in the form of rods.

Major limitations: - Outlet temperature of the gas ~ 400°C,
- High reactivity of magnesium alloy with water.

AGR nuclear reactor: - metallic uranium enriched (2.0% - 2.5%),
- stainless steel cladding.

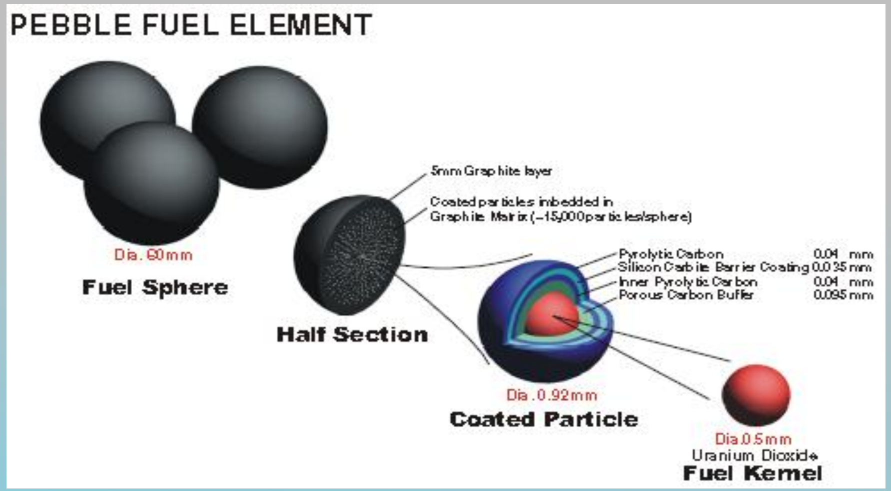
Característica	OLDBURY (GCR) (por reator)	DUNGENESS-B (AGR) (por reator)
Potência Elétrica, MW (e)	300	600
Combustível	U. Natural (0,7%)	U. Enriquecido (~2,5%)
"Core" ativo:		
Diâmetro, M	12,8	9,5
Altura, m	8,5	8,3
Volume, m³	1.093,000	588,000
Potência Elétrica/litro de "Core" Ativo, em kw(e)/litro	0,27	1,02
Número de Canais	3.320	465
Pressão de Trabalho, kg/cm²	25,7	30,6
Temperatura de Entrada, °C	245	320
Temperatura de Saída, °C	412	675
Máxima Temperatura do Cladding, °C	480	800
Material do Cladding	MAGNOX	AÇO INOXIDÁVEL
Passo (distância entre os eixos de canais adjacentes), cm	19,7	39

- Outlet temperature of the gas to the range of 650°C,
- Increased burnout for 3000 to 18000 MWd/t

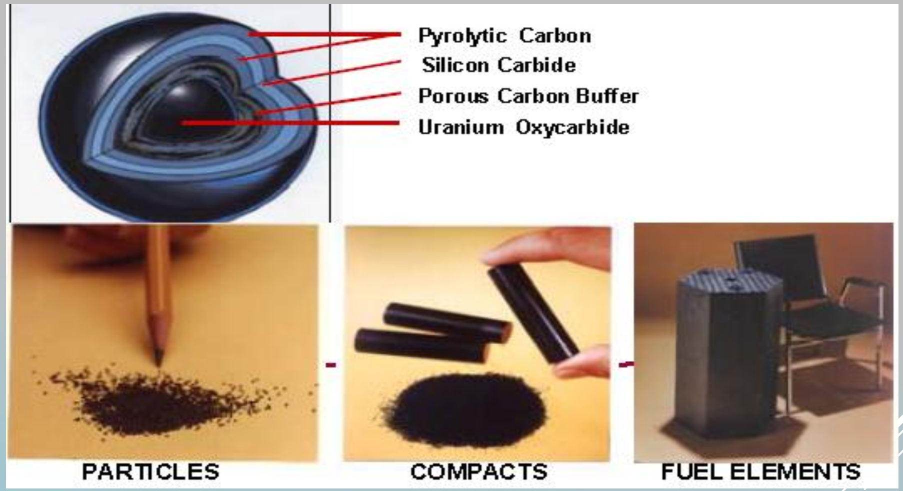
HTGR (High Temperature Gas Reactor): - Helium (He) as coolant,
- fuel particles with 2 (BISO) or 3 (TRISO) layers.

Two different technologies:

- Pebble Bed: fuel element sphere-shaped with 6cm of diameter.



- Fuel element in hexagonal prism shape.



Helium gas allows high output temperatures of the coolant ~780°C.

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Parâmetro	Unidade	Valores
Potência Térmica	MW (t)	46
Potência Elétrica	MW (e)	15
Elemento Combustível	–	Esferas com 6cm (diâmetro)
Dimensões do "Core"		
Diâmetro	cm	300
Altura (cilindro)	cm	250
Número de Elementos Combustíveis	–	95.000
Densidade de Potência, Média	MW/m^3	2,2
Pressão de Trabalho (Hélio)	atm	10
Temperatura de Saída	°C	850

Característica	Unidade	Valor
Potência Térmica	MW (t)	842
Potência Elétrica	MW (e)	330
Dimensões do "Core" (ativo)		
Diâmetro	m	5,90
Altura	m	4,70
Número de Elementos Combustíveis	–	1.482
Pressão do Refrigerante (Hélio)	kg/cm^2	46,8
"Burnup"	MWd/t	~ 100.000
Densidade de Potência, média	kw/litro	6,3
Temperatura de Saída	°C	770

↑ Output temperatures

\+

↑ Power (cheaper fuel)

=

↑ Efficiency

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Generation IV Nuclear Reactors [6]:

The main objectives can be grouped into four areas:

- Sustainability (use of fuel resources with waste minimization),

- Economics (competitiveness in fuel cycle costs and low risks for the capital),

- Security and reliability: > Safety and Reliability
  > Risk of damage to the reactor core extremely small
  > Unnecessary external emergency response to incidents

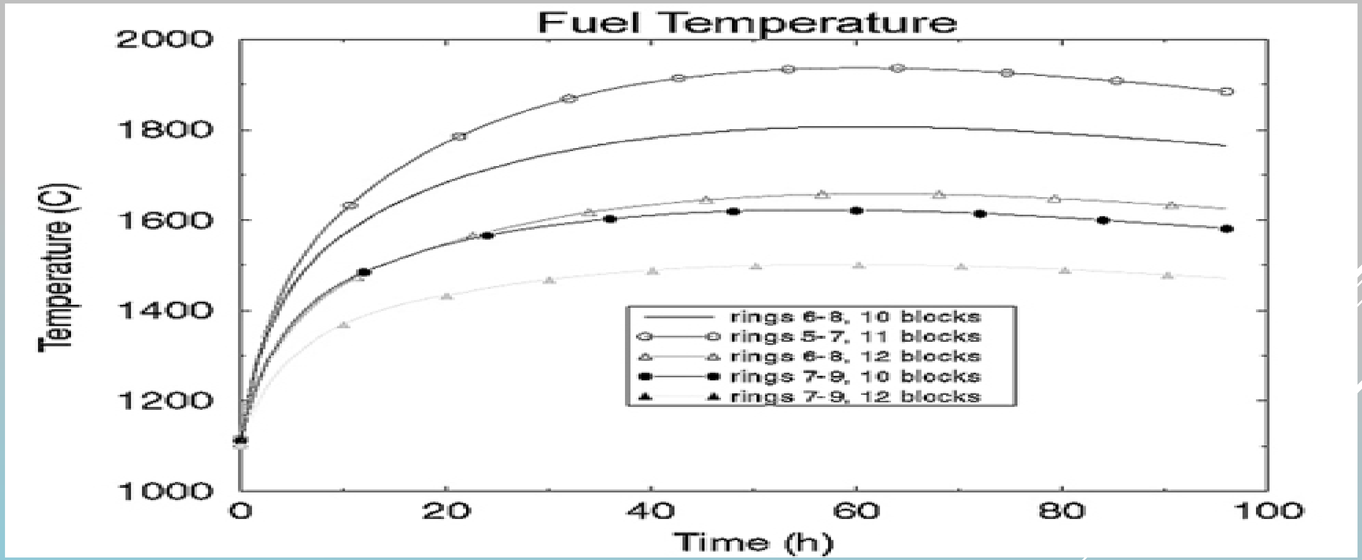
- Proliferation resistance and physical security

6 news concepts of reactors – VHTR is one of them.

VHTR: - Helium as coolant,
- Graphite moderated,
- Ceramic core with TRISO particles,
- Meet the goals of Gen. IV reactors,
- Increased output temperature to 1000 - 1200°C (important for industrial processes and Hydrogen production).

<u>Advantages:</u>

> Ceramic core with high thermal capacity, capable of withstanding extremely high temperatures under accident conditions.
> Negative coefficient of reactivity



[3]

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- Advantages of Helium: Chemically and neutronically inert, besides not undergoing a phase change at or above the operating temperature of the reactor.

- TRISO particles: each fuel particle is essentially its own pressure container able to retain fission products.

Gas cooled reactors are able to retain fission products effectively and <u>are designed to prevent radioactive release</u> without operator intervention or active safety systems.

- No need for containment building, reducing capital costs.

- Future VHTR can be constructed in areas with dense population or industrial zones.

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Safety Aspects:

Active System X Passive System

Systems that rely on some type of energy source to operate.

Systems that do not need external sources of energy to operate. Use the very laws of nature, such as gravity, heat transport by conduction, convection and radiation, etc..

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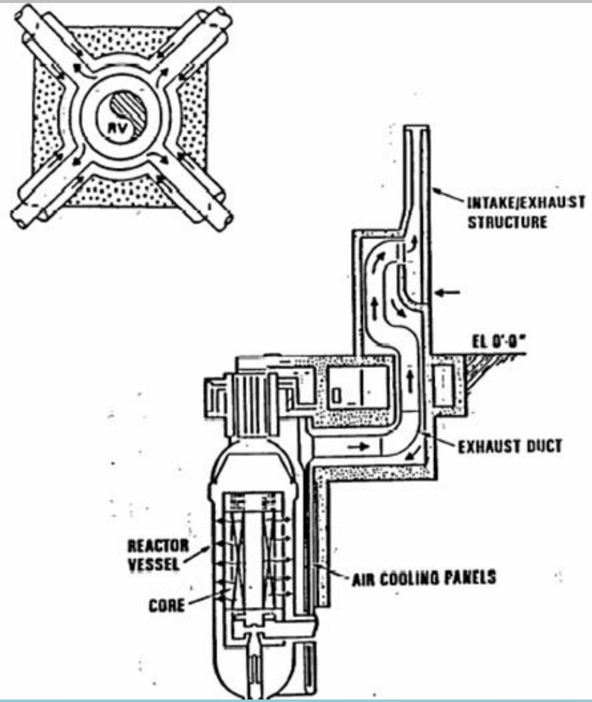
For removing heat from the core are used these two kinds of systems:

1) The Power Conversion Unit, active system, in normal operation.

2) Shutdown Cooling System - SCS, active system for normal stopping conditions.

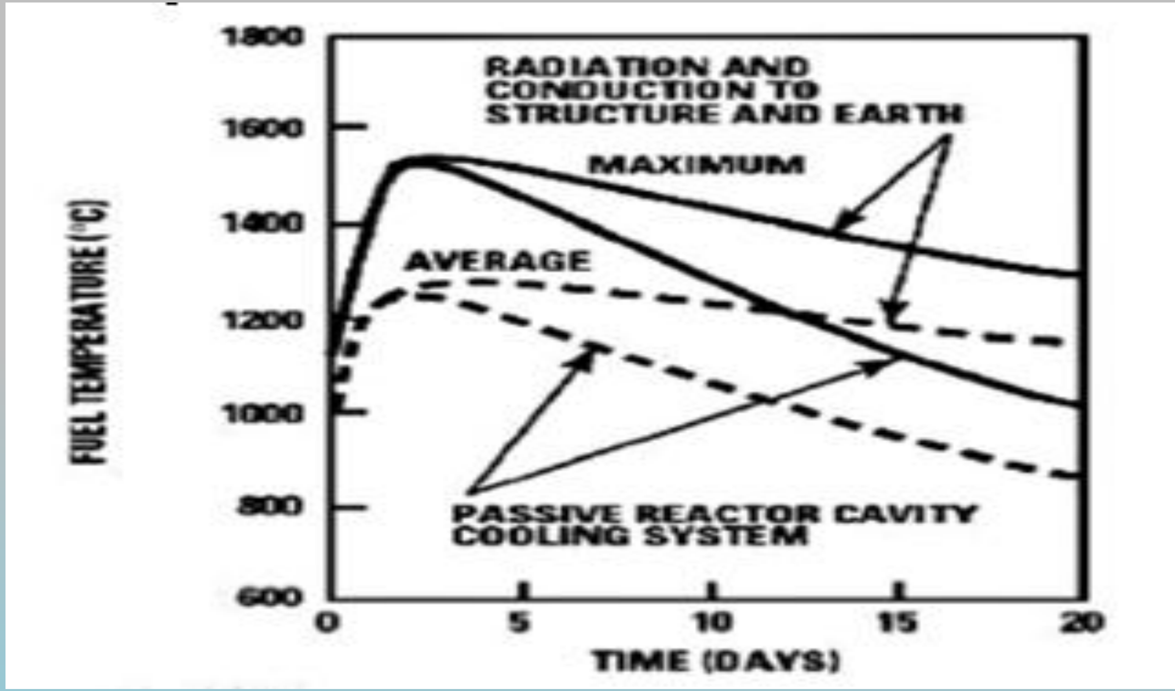
3) Reactor Cavity Cooling System - RCCS, passive system for heat removal in accident conditions (safety system). [3]

With cooling panels and ducts that allow the natural circulation of the air.



- If the natural circulation is established properly, the RCCS ensures that the accidents are not exceeded the maximum temperature limits.

- The maximum temperatures are reached about 2 days (48 hours), giving time to make repairs, the reestablishment of the grid and/or the evacuation of the population.



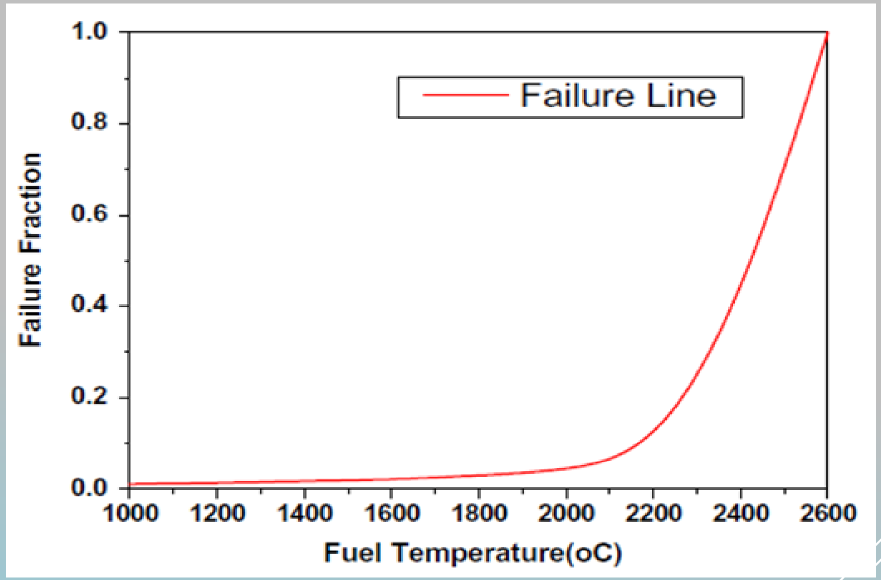
Comparison between the fuel temperature with and without the RCCS.

Reliability Analisys of Passive Systems:

- The natural circulation driving forces is weak and its performance is sensitive to material properties and deviations in the boundary conditions, among other factors.

- The reliability analysis evaluates the performance of this passive system, by sensitivity studies, determining the probability that the maximum fuel temperature exceeds the limit value set as the criterion of success.

[13]



[14]

RCCS Reliability Analysis:

In a 600MWt power reactor, is performed a sensitivity analysis of the maximum temperature (Tmax) of the fuel as a result of an accident with depressurization of the reactor, varying the parameters of heat capacity and thermal conductivity of graphite:

100% (1,0) of ρCp and K: References Conditions

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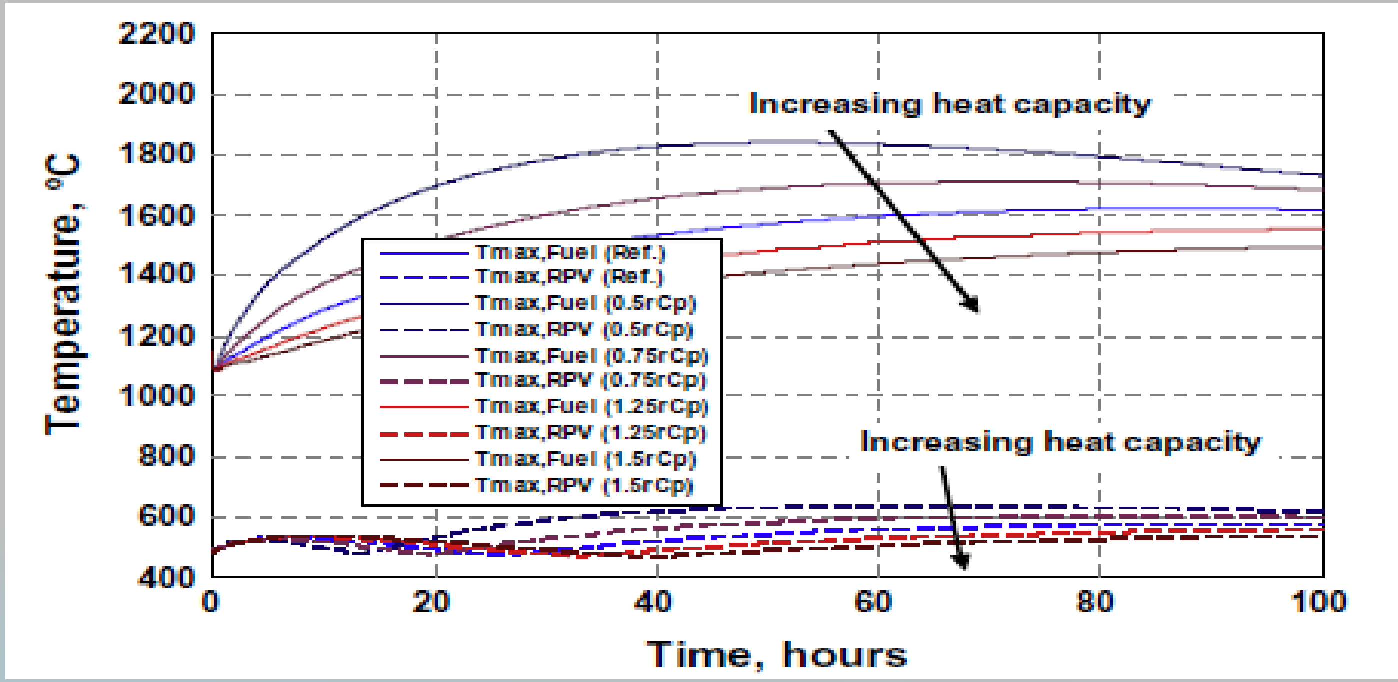
Variation from 50%-150% (0,5~1,5) of ρCp – K in the reference condition:



RoCp / (RoCp)ref	Tcomb
0,5	1850
0,75	1720
1	1620
1,25	1560
1,5	1490

[14]

- Volumetric heat capacity (ρCp) increases:
  - Increase the heat absorbed by graphite,
  - Increase of thermal inertia, the response time for big temperature changes is delayed.

Variation from 50%-150% (0,5~1,5) of K - ρCp in the reference condition:

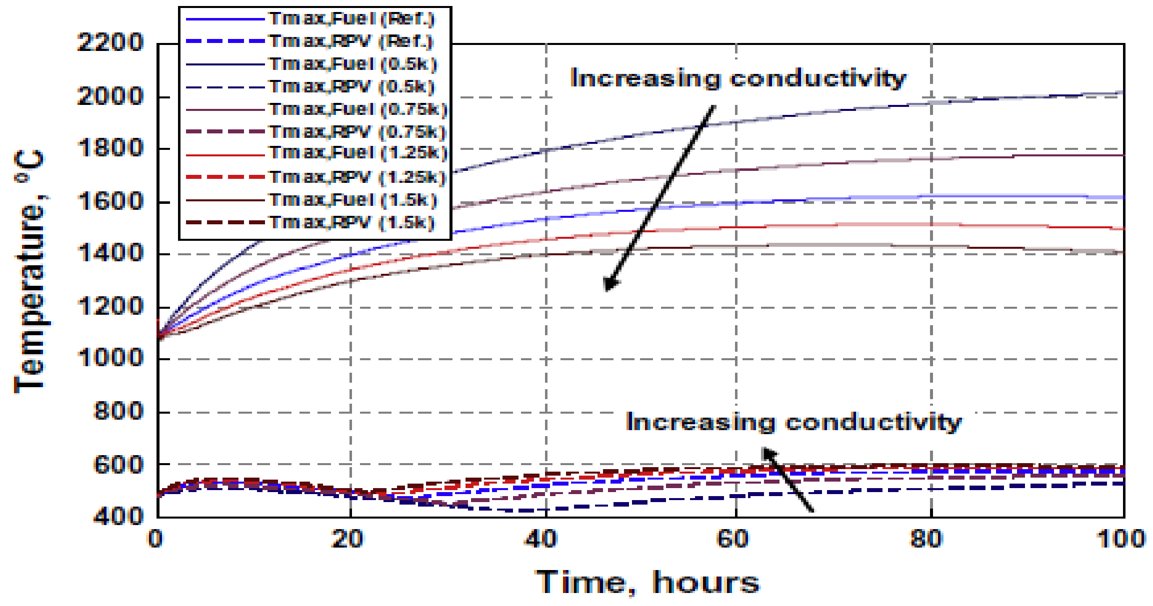


Fig. 7. Maximum temperature characteristics in varying thermal conductivity.

k / kref	Tcomb
0,5	2020
0,75	1790
1	1620
1,25	1510
1,5	1440

[14]

- Increased thermal conductivity of graphite:
- Increased heat transfer from the core to the pressure vessel and then into the RCCS.
- Reduction of the maximum temperature of the fuel.

RoCp / (RoCp)ref	k / kref	Tcomb
0,5	1	1850
0,75	1	1720
1	1	1620
1,25	1	1560
1,5	1	1490
1	0,5	2020
1	0,75	1790
1	1,25	1510
1	1,5	1440

$$Tcomb = 2595 - 352\,(RoCp) - 576\,k$$

- Table with data combined and linear regression equation with two parameters (ρCp and K).

- The Monte Carlo method was applied to determine the statistical parameters of the fuel maximum temperature distribution, based on 5000 random values generated for ρCp and K.

- It is considered normal distribution for ρCp and K.

- Knowing the statistical parameters of the fuel maximum temperature (1667°C, 59,69°C) was determined the probability of exceeding the safety limit established for this temperature under accident conditions.

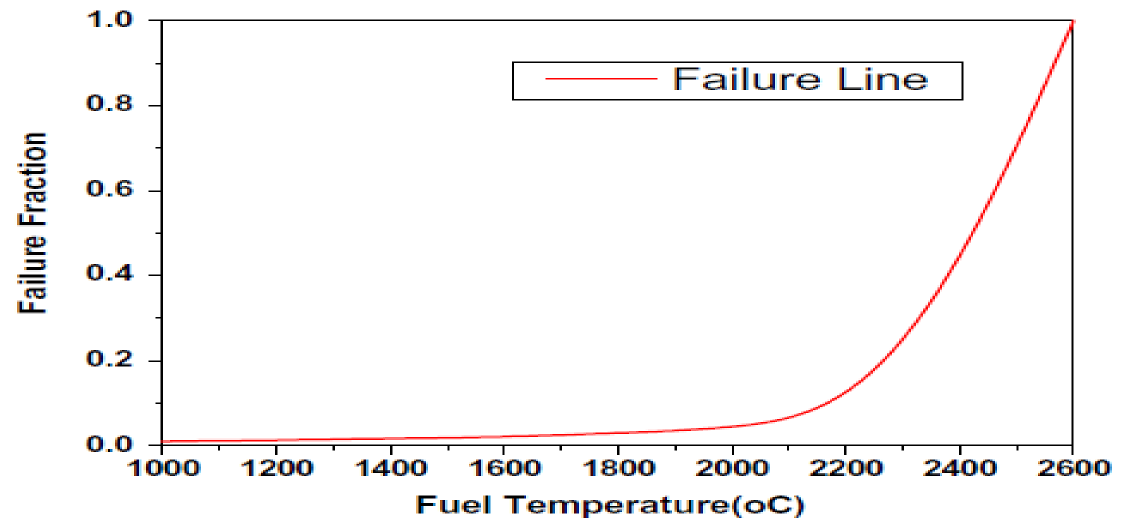


Fig. 6. Fuel temperature vs. failure fraction.

- Analyzing the graphic fuel temperatures X failure fraction and combining the results, it was obtained:

Tmax	P = Prob (Tcomb>Tmax)	F = Fração de falhas	P*F
1600	0,87076901	0,03	0,02612307
1700	0,292750067	0,035	0,010246252
1800	0,013183248	0,04	0,00052733
1900	4,88623E-05	0,045	2,1988E-06
2000	1,26223E-08	0,05	6,31116E-10

- **Prob (Fuel temperature > 2000°C) = 1,262e-8**
- **Failure fraction = 0,0368**

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Conclusions:

- Importance of Reliability analyzes of passive systems.

- A general methodology of the passive system of reliability was applied to a natural circulation safety cooling system of an IV Generation (VHTR) nuclear reactor project.

- The results confirmed the existing inherent security of this reactor type, so that for the most critical accidents there is a very low risk of important radiation release into the environment (probability < 1,26E-8 of T > 2000°C, with fuel failure fraction >5%).

- There were analyzed two factors (ρCp, K) but there are others important ones such as geometric variations of the environment temperature and the materials thermal emissivity.

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Thank you.

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Bibliography:

[1] B J Marsden - Nuclear Graphite Reserach Group School of Mechanical, Aerospace and Civil Engineering, The University of Manchester.

[2] Costa, Jose Ribeiro - CURSO DE INTRODUÇÃO À TECNOLOGIA DO HTGR (High Temperature Gas - Cooled Reactor) – 1972

[3] Chapin, Doug; Kiffer, Scott; Nestell, Jim - *The Very High Temperature Reactor: A Technical Summary* – Junho 2004

[4] Dr. BÖCK, H. - Vienna University of Technology /Austria

[5] Gen IV – International Forum – Proceedings – GIF Symposium – Paris, France – 9 and 10 September – 2009

[6] Gen IV – International Forum – Annual Report 2011

[7] Generation IV Gas-cooled Reactor - System Concepts -Technical Working Group 2 -- Gas Cooled Reactor Systems -Generation IV Roadmap Session - ANS Winter Meeting Reno, NV - November 13, 2001

[8] High Temperature Gas Reactors - Andrew C. Kadak, Ph.D., *Professor of the Practice* Massachusetts Institute of Technology

[9] McKeen, Tim – Advanced Gas Cooled Reactors - ADI Limited, Fredericton, Canada

[10] http://www.enotes.com/topic/List_of_nuclear_reactors

[11] Murphy, B. D. - ORIGEN-ARP Cross-Section Libraries for Magnox, Advanced GasCooled, and VVER Reactor Designs – February 2004

[12] Nuclear Engineering Division, num trabalho titulado "*Priorization of VHTR System Modeling Needs Base on Phenomena Identification, Ranking and Sensitive Studies*", by Vilim, W. D. Pointer, T. Y. C. Wey – April 2006

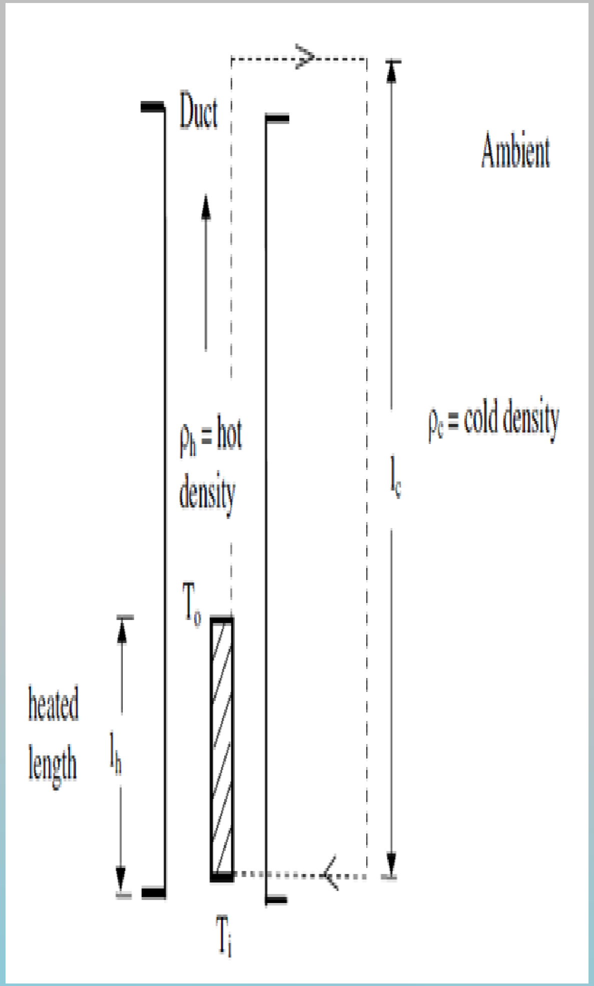
[13] Seok-Jung Han, Joon-Eon Yang. A quantitative evaluation of reliability of passive systems within probabilistic safety assessment framework for VHTR. Annals of Nuclear Energy 37, 2010

[14] Tae-Ho Woo, Un-Chul Lee, Dynamical reliability of the passive system in the very high temperature gas cooled reactor, Annals of Nuclear Energy, Department of Nuclear Engineering, Seoul National University, Gwanak 599, Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea. 17 July 2009.

[15] Tawil, Elie – Fluid Flow – June1992

[16] The Very High Temperature Reactor: A Technical Summary - *Principal Contributors* Doug Chapin, Scott Kiffer, Jim Nestell – June 2004

Appendix:



Loss of load:

$$\rho_c\beta\left(\frac{l_c}{l_h}-\frac{1}{2}\right)h_{tc}\Delta T=\left(2\frac{f}{D_h}\frac{l_c}{\bar{\rho}}+\frac{1}{\rho_c}\left(\frac{\beta\Delta T}{1-\beta\Delta T}\right)+\frac{1}{2}\left(\frac{K_i}{\rho_c}+\frac{K_o}{\rho_h}+\frac{K_{orf}}{\rho}\right)\right)G^2$$

[15]

A (m^2)	W (kg/s)	ΔT (C)	ρ (kg/m^3)	l_h (m)	B (1/C)	l_c (m)	h= l_c-1/2l_h (m)	D_h (m)
0.05*0.25	0.049	225	0.83	16	0.0023	34	26	0.083

Gravity, Pa	$gh(\rho_{out}-\rho_{in})=gh\rho_{in}\,\beta\Delta T$	$9.8\cdot 26\cdot 0.83\cdot 0.0023\cdot 225=108$	
Acceleration, Pa	$\frac{W^2}{A^2}\left(\frac{1}{\rho_{out}}-\frac{1}{\rho_{in}}\right)=\frac{W^2}{\rho_{in}A^2}\left(\frac{1}{1-\beta\Delta T}-1\right)$	$\frac{0.049^2}{0.83\cdot(0.05\cdot 0.25)^2}\left(\frac{1}{1-0.0023\cdot 225}-1\right)=20$	Sum=133
Friction, Pa	$4f\frac{l_c}{D_h}\rho\frac{v^2}{2}=4f\frac{l_c}{D_h}\frac{1}{2\rho}\left(\frac{W}{A}\right)^2, f=\frac{0.079}{Re^{0.25}}$	$\frac{4\cdot 0.079}{14{,}000^{0.25}}\frac{34}{0.083\cdot 2\cdot 0.83}\left(\frac{0.049}{0.05\cdot 0.25}\right)^2=109$	
Entrance and Exit Loss, Pa	$2K\frac{1}{2\rho}\left(\frac{W}{A}\right)^2$	$\frac{0.2}{0.83}\left(\frac{0.049}{0.05\cdot 0.25}\right)^2=4$	

Negative coefficient of reactivity

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Appendix:

Table E.1
The selected uncertainty parameters and their ranges.

Uncertainty parameter	Units	Nominal value[a]	Range[b]	Standard deviation[c]	Distribution type	Remark
Graphite heat capacity	kJ/kg K m^3	1.0	0.95 1.05	0.025511	Normal	Function of temperature and pressure
Graphite conductivity	W/(m K)	1.0	0.8 1.2	0.102043	Normal	Function of temperature
Vessel emissivity		0.8	0.72 0.88	0.040817	Normal	
RCCS tube emissivity		0.8	0.72 0.88	0.040817	Normal	
Core effective conductivity multiplier		1.0	0.9 1.1	0.051021	Normal	
Decay heat ratio	%/full power	1.0	0.95 1.05	0.025511	Normal	Function of normal reactor power

[a] The nominal value is a representative value of the GAMMA code lookup table.
[b] The range assigned 95% confidence boundary of a normal distribution.
[c] The standard deviation can be estimated by $\sigma_X = |X_R \quad \mu_X|/Z_{0.95}$ where $Z_{0.95} = 1.95996$, X_R is a range value and μ_X is a nominal value in this table.

[13]