

## **Thermal-hydraulic modelling and state analysis of a LS-VHTR reactor**

### **Modelagem térmico-hidráulica e análise do estado de estado de um reator LS-VHTR**

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#### **Mario Cerrogrande Ramos**

Doctor in Nuclear Sciences and Techniques

Institution: Universidade Federal de Minas Gerais, Agencia Boliviana de Energia Nuclear

Address: Av. Arica, entre calles 22407 y Punata, Urbanización Parcopata, Distrito 8, El Alto

E-mail: marc5663@gmail.com

#### **Antonella Lombardi Costa**

Doctor in Nuclear and Industrial Security

Institution: Universidade Federal de Minas Gerais

Address: Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte – MG, CEP: 31270-901

E-mail: antonella@nuclear.ufmg.br

#### **Maria Auxiliadora Fortini Veloso**

Doctor of Chemical Engineering

Institution: Universidade Federal de Minas Gerais

Address: Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte – MG, CEP: 31270-901

E-mail: mdora@nuclear.ufmg.br

#### **Cláudia Pereira Bezerra Lima**

Doctor in Environment and Nuclear Safety

Institution: Universidade Federal de Minas Gerais

Address: Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte – MG, CEP: 31270-901

E-mail: claudia@nuclear.ufmg.br

#### **Mabel Bustos Flores**

Doctor in Nuclear Sciences and Techniques

Institution: Universidade Federal de Minas Gerais, Agencia Boliviana de Energia Nuclear

Address: Av. Arica, entre calles 22407 y Punata, Urbanización Parcopata, Distrito 8, El Alto

E-mail: mabelita.bfm@gmail.com

#### **ABSTRACT**

The Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR) is a liquid salt cooled and TRISO fueled reactor, which presents very good features in terms of power production and safety aspects. The advantage of using liquid salt as coolant is mainly related with its high efficiency of heat transfer and operation at low pressures. This work

evaluates the thermal hydraulic performance of the heat removal system and the reactor core, in steady state conditions, starting from the single channel level and concluding with the full core model. The LS-VHTR is a new reactor concept that introduces some different features in relation to other nuclear reactors. In this way, a thermal modeling of this reactor has been developed using the RELAP5-3D code using a point kinetic model. A modeling with three channels has been presented. The core coolant temperature increase, the core coolant mass flow and the pressure along the core were simulated and presented in good agreement with the expected behavior

**Keywords:** LS-VHTR, RELAP5-3D.

## RESUMO

O Reator de Muito Alta Temperatura Resfriado por Sal Líquido (LS-VHTR) é um reator resfriado por sal líquido e alimentado por TRISO, que apresenta características muito boas em termos de produção de energia e aspectos de segurança. A vantagem de utilizar sal líquido como refrigerante está relacionada principalmente com sua alta eficiência de transferência de calor e operação em baixas pressões. Este trabalho avalia o desempenho termo-hidráulico do sistema de remoção de calor e do núcleo do reator, em condições estacionárias, partindo do nível de canal único e concluindo com o modelo de núcleo completo. O LS-VHTR é um novo conceito de reator que apresenta algumas características diferentes em relação a outros reatores nucleares. Desta forma, foi desenvolvida uma modelagem térmica deste reator utilizando o código RELAP5-3D utilizando um modelo cinético pontual. Foi apresentada uma modelagem com três canais. O aumento da temperatura do refrigerante no núcleo, o fluxo de massa do refrigerante no núcleo e a pressão ao longo do núcleo foram simulados e apresentados em boa concordância com o comportamento esperado

**Palavras-chave:** LS-VHTR, RELAP5-3D.

## 1 INTRODUCTION

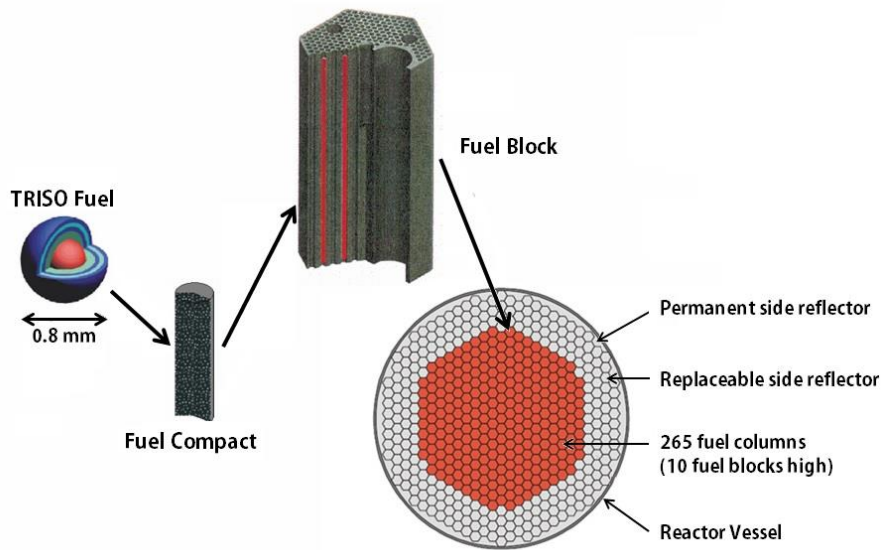
The Liquid-Salt-Cooled Very-High-Temperature Reactor (LS-VHTR) is a variant of the gas-cooled very high-temperature reactor (VHTR) concept and combines several new technology assets such as successful use of coated-particle graphite-matrix fuel in helium-cooled reactors; reactor plant and safety systems similar to that developed to the liquid-metal cooled fast reactors; low-pressure liquid-salt coolants studied and researched for liquid fuel reactors; and Brayton power cycles at high-temperatures. The LS-VHTR project goal is to provide an advanced design which offers the potential for higher power output, improved efficiency of electricity production, and higher operating temperatures leading to significant reduction in plant capital costs, as well as its use in high-temperature process heat applications that can economically produces hydrogen [1].

The LS-VHTR core uses coated-particle graphite-matrix fuel have uranium oxycarbide fuel kernels which is coated with multiple layers of pyrolytic carbon and silicon carbide to form a microsphere of 0.8 mm diameter that prevents release of radionuclides at very high temperatures. These microspheres fuel are frequently referred to as “TRISO” fuel and are incorporated into a graphite-matrix fuel compact, which, in turn is loaded into a hexagonal fuel block, which provides more control of the fuel and coolant volume fractions and geometry. Fig. 1 shows the TRISO fuel and a typical fuel compact and prismatic graphite block, which is the fuel assembly shape utilized in the LS-VHTR.

A total of 265 columns of fuel blocks are assembled into a cylindrical geometry with nonfueled graphite reflector blocks filling in the region between the outer diameter of the core and the reactor vessel. Fig. 1 provides a plan view of the core and reflector geometry. This cylindrical shape improved neutron economy, heat transfer, transport of liquid coolant and increase the total power output compared with the VHTR gas-cooled. LS-VHTR uses a closed primary cooled loop immersed in a tank containing a separate buffer salt. This design allows the use of a better salt in the primary coolant loop, that is, a salt that have better coolant properties but is not so good financially [2].

The advantages of using liquid salt as coolant is mainly related with its high efficiency for heat transfer, operation at low pressures, high volumetric heat capacity compared to gas and sodium, possible optical inspection and low corrosion rate. A drawback aspect of liquid salts is the high melting temperature (between 350°C and 450°C), however, since the reactor operates at high temperature, this is not a problem. The salt used for coolant is called Flibe (66% LiF and 34% BeF<sub>2</sub>). The Flibe has a small neutron cross section, which makes it relatively transparent to neutrons [3].

Figure 1: Design of the LS-VHTR core.

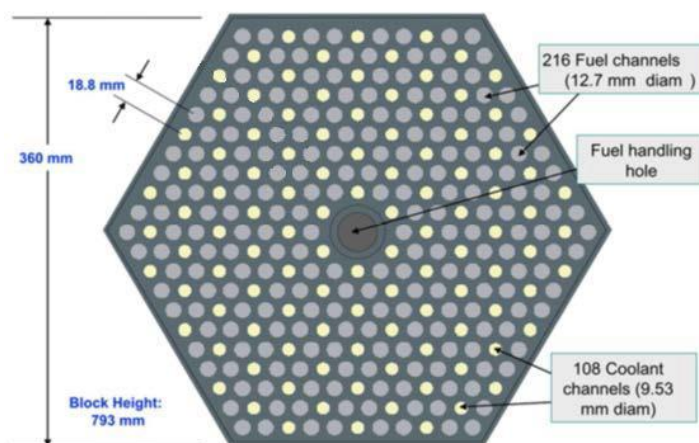


Source: Adapted from D. T. Ingersoll et al. 2005.

## 2 METHODOLOGY

In this study the baseline fuel block design considered is the same as that considered in the work of Davis and Hawkes, 2006. Each fuel block consists of a hexagonal element of 216 fuel channels, with diameter of 12.7 mm, 108 coolant channels with diameter 9.53 mm and a fuel handling hole. The flat-to-flat distance of the block is 360.0 mm and the channel pitch is 18.8 mm. The baseline block is shown in Fig. 2. The geometrical parameters used in this study are presented in Tab. 1 [2].

Figure 2: The LS-VHTR block.



Source: Adapted from D. T. Ingersoll et al. 2007.

Table 1: Geometrical parameters of the LS-VHTR.

Parameter	Value
Coolant channel diameter	9.53 mm
Fuel compact diameter	12.45 mm
Fuel channel diameter	12.7 mm
Fuel channel pitch	18.8 mm
Number of coolant channels per block	108
Number of fuel channels per block	216
Number of fuel columns	265
Flat-to-flat distance of hexagonal blocks	360 mm
Gap between hexagonal blocks	1.0 mm
Heated length	7.93 m

Source: Adapted from D. T. Ingersoll et al. 2007.

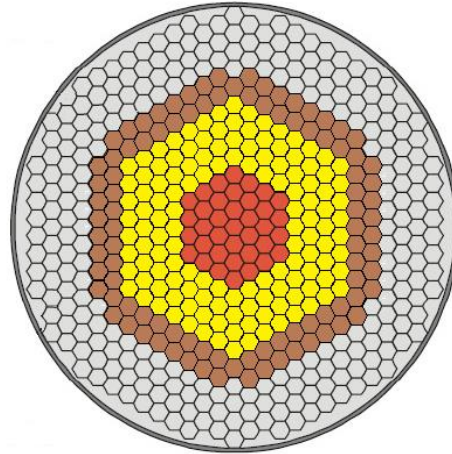
An initial thermal analysis of the LS-VHTR was performed in a previous work [4] where the simulation of only one unit cell was considered in the RELAP5-3D code. Each unit cell, represented as a part of the hexagonal fuel block, was modeled to represent one coolant channel, filled with Flibe, and two fuel channels, with two gaps, immersed in graphite moderator matrix [4,5]. In the present work, the unit cell was repeated throughout the active part of the core and this representation to model the core reactor, a thermal modeling by this reactor has been developed using the RELAP5-3D code using a point kinetic model. The core inlet and outlet coolant temperatures, the coolant mass flow, pressure drop and the temperatures along the core were simulated. The results have been compared with the available data. The developed model demonstrated that the RELAP5-3D is capable of reproduce the thermal behavior of the LS-VHTR in steady state operation.

RELAP5-3D code can employ a variety of coolants in addition to water, the original coolant employed in early versions of the code. Liquid metals (sodium, potassium, NaK, lithium, Flibe) and cryogenic fluids (hydrogen, helium, nitrogen) are some of the available coolants [6]. In this way, the RELAP5-3D can appropriately simulate high temperature reactors. The RELAP5 code versions were originally designed to simulate light water reactors (LWR). The hydrodynamic model is a two-fluid model for flow of a two-phase steam-water mixture that allows non condensable components as, for example, helium, in the steam phase and/or a soluble component in the water phase. In this way, it is possible to use RELAP5 with only helium and no steam, as in the case of a HTR simulation.

In this way, the LS-VHTR core has been modeled using the RELAP5-3D code. In the developed model, 3 thermal hydraulic channels (THC) represent three regions across the core as shown in Fig. 3. The inner region groups the rings 1, 2, 3 and 4. The rings 5,

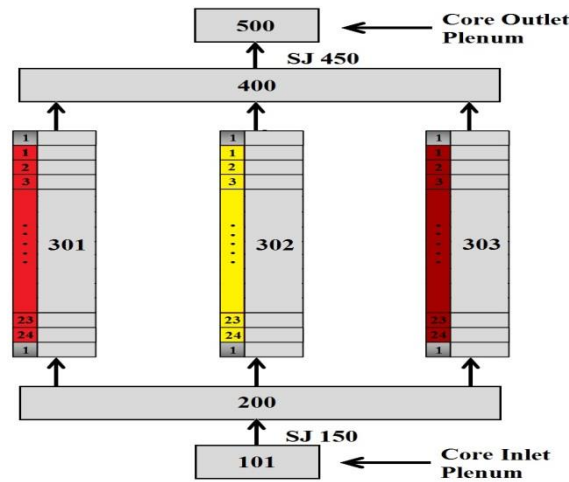
6, 7 and 8 constitute the middle region. The outer region is composed of the two outer rows of fuel assemblies; rings 9 and 10. A summary of the characteristics of the groups is given in Tab. 2.

Figure 3: Inner, middle, and outer region of the LS-VHTR core.



Source: Adapted from D. T. Ingersoll et al. 2005.

Figure 4: LS-VHTR core reactor modeled in the RELAP5-3D.



Source: own elaboration

Table 2: Description of the model core regions.

	Group 1	Group 2	Group 3
Number of assemblies in the region	37	132	96
Fraction of total number of assemblies	14 %	50 %	36 %
Power generated by the region	447.2 MW	1277.8 MW	674.1 MW
Fraction of total power	18.6 %	53.2 %	28.1 %
Peak to average radial factor	1.33	1.07	0.78

Source: own elaboration

The complete core model is illustrated in Fig. 4. The coolant channels were represented by the component of the type pipe and were divided in 24 axial volumes of

0.3304 m corresponding to the active length of 7.93 m. Two time dependent volumes, 101 and 500, represent, respectively, the inlet and outlet core plenum. The components 450 and 150 are single junctions and the pipes from 301 up to 303 represent the coolant channels.

The Heat Structure (HS) simulate the power source of each channel and they were divided axially according to the same quantity of the thermal channel volumes. All HS have 12 radial meshes, being 6 intervals to the fuel region, 1 interval for the helium gap and 4 intervals representing the graphite region. The thermodynamics properties of the LiF-BeF<sub>2</sub> were selected to perform the calculations and the effective thermal conductivity (ETC) properties of the compact fuel were determined by the same way as in the reference work [7] and [8] using the full version of the Maxwell's equation. The point kinetics option was used in the calculations, the data of volumetric heat capacity and heat transfer coefficient of the standard fuel compact, the helium in the gap and the graphite were considered. The initial conditions used to simulate the core are shown in Tab. 3.

Table 3: Initial conditions for the LS-VHTR.

Parameter	Value
Core total power	2400 MW
Core mass flow rate	10,264 kg/s
Core inlet temperature	900 °C
Core outlet temperature	1000 °C
Core pressure drop	0.211 MPa

Source: Adapted from D. T. Ingersoll et al. 2007.

The radial power distribution profile used in this work was calculated by ORNL [1] and is shown in Fig. 5. This distribution was generated using Monte Carlo code MCNP4C or a 10-ring core model. The axial power profile chosen is based on a profile used by ORNL to model the LS-VHTR [2,9] and is shown in Fig 6. Both radial and axial normalized power factors (called multiplication factors) are specified for each axial segment in the heat structures that are coupled to the thermal hydraulic channels that shape the reactor core. The normalization is performed according to the number of THC simulated in the case of radial power factors, and normalized according to the number of axial meshes, and in the case of axial power factors. These factors are characterized by subscripts representing the radial region number “g” in the reactor core and subscripts representing the axial position “i”. The partial power  $P_{gi}$  supplied in the axial segment “gi” in the heat structure is given by Eq. 1:

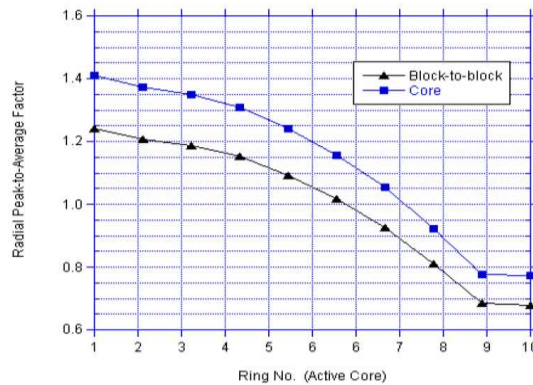
$$P_{gi} = f_g f_{gi} P_{total} \tag{1}$$

Where:

$f_g$  is the normalized radial power factor,  $f_{gi}$  is the normalized axial power factor, and  $P_{total}$  is the total reactor core power. The sum of the multiplication of these normalized factors must equal unity.

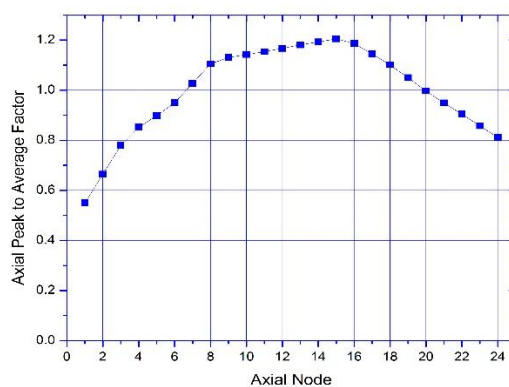
The nodalization consisted of modeling each active ring of each reactor with THC as can be seen in Figure 3, considering that the active core has different types of fuel blocks. The coolant flow in each region was modeled by THC coupled with their respective heat structures.

Figure 5: Radial power profile for the 10-ring ORNL LS-VHTR.



Source: Adapted from D. T. Ingersoll et al. 2007.

Figure 6: Axial power profile for the 24 nodes ORNL LS-VHTR.



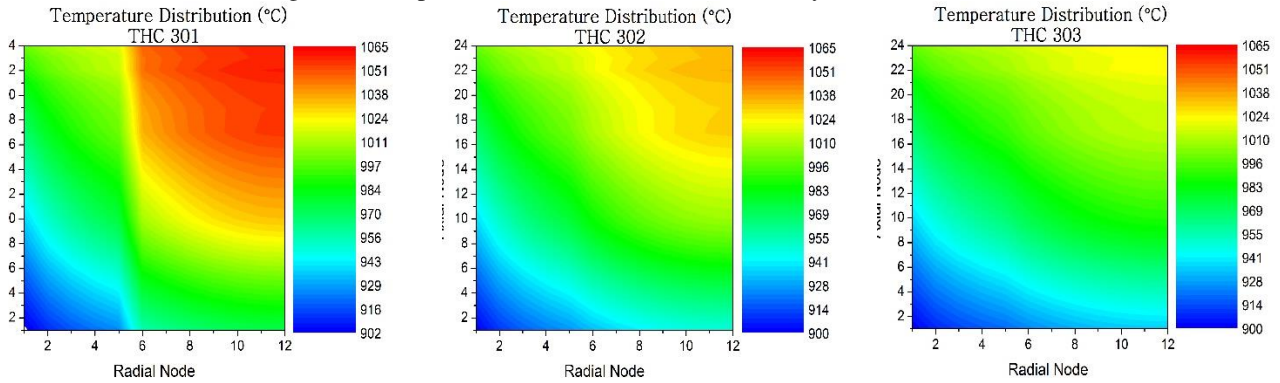
Source: Adapted from P. E. MacDonald. 2005.

### 3 RESULTS

The temperature distribution along the reactor core in the 3- thermal hydraulic channels modeling is illustrated in Figure 7, where the temperature for each axial and radial node of the THCs are plotted. The temperature decreases in each thermo-hydraulic

channel from 301 to 303. The behavior of the distribution temperature in each channel has regions with higher temperatures located in the upper part of each heat structure, with the maximum fuel temperatures of 1050 °C, 1029 °C and 1018 located in axials 22, 23 and 24, respectively.

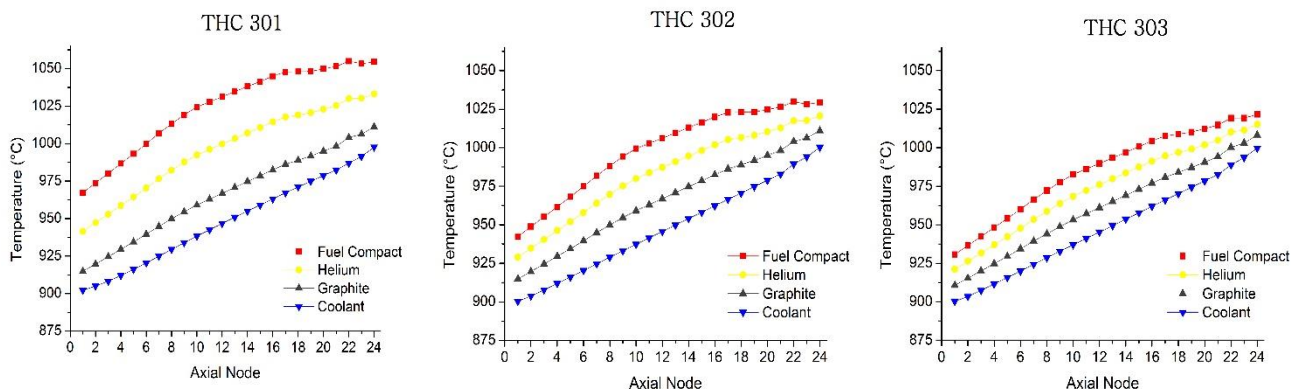
Figure 7: Temperature distribution of the thermal hydraulic channels.



Source: own elaboration

The temperature distribution axially along the THCs are shown in the Figure 8. Each point represents an axial node of the structure, from 1 up to 24 (1 is the bottom and 24 is the top). The temperature distribution has the same fuel shape as the reference axial power profile, which smooths out quickly along the channels and in each material of the heat structure and in the coolant.

Figure 8: Temperature distribution axially along the THCs.

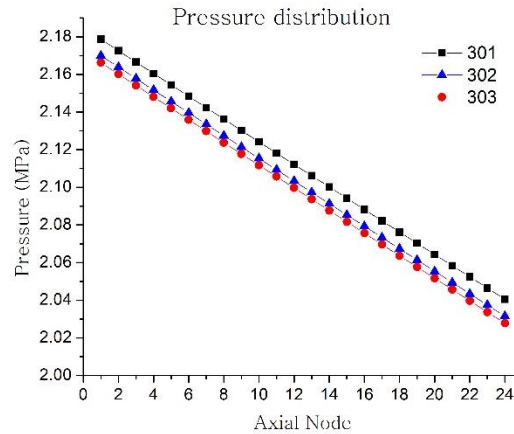


Source: own elaboration

The pressure behavior along the thermo-hydraulic channels is shown in Figure 9, the pressure have the same behavior along in each THC and decreases linearly from axial 1 to axial 24. The pressure drop obtained by the calculation in this work is 0.18 MPa,

which is very close to the pressure drop from the reference data (0.21 MPa as shown in Tab. 3). This difference may be due to the configuration the heat structure.

Figure 9: Pressure distribution of the heat structure.



Source: own elaboration

#### 4 CONCLUSIONS

Core thermal analysis of the LS-VHTR reactor has been performed in this study using the RELAP5-3D code for a steady state simulation. The simulations of the thermal parameters of the reactor cooled by liquid Li<sub>2</sub>BeF<sub>4</sub> (Flibe) salt presented similar behavior in relation to those of the reference data.

The comparison between the simulated results and the reference data demonstrate that the developed model is capable to reproducing the thermal behavior of the reactor in steady state operation. More investigations are necessary mainly in relation to the heat transfer between the components of the heat structures. Future work consists in to incorporate more reactor details beyond the core in the model and also to simulate transient events.

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