2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
***ISBN*: 978-85-99141-05-2**

A Coupled Nuclear Reactor Thermal Energy Storage System for Enhanced Load Following Operation

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ABSTRACT

Nuclear power plants operate most economically at a constant power level, providing baseload electric power. In an energy grid containing a high fraction of renewable power sources, nuclear reactors may be subject to significantly variable power demands. These variable power demands can negatively impact the effective capacity factor of the reactor and result in severe economic penalties. Coupling a nuclear reactor to a large thermal energy storage block will allow the reactor to better respond to variable power demands. In the system described in this paper, a Prismatic–core Advanced High Temperature Reactor supplies constant power to a lithium chloride molten salt thermal energy storage block that provides thermal power as needed to a closed brayton cycle energy conversion system. During normal operation, the thermal energy storage block stores thermal energy during the night for use in the times of peak demand during the day. In this case, the nuclear reactor stays at a constant thermal power level. After a loss of forced circulation, the reactor reaches a shut down state in less than half an hour and the average fuel, graphite and coolant temperatures remain well within the design limits over the duration of the transient, demonstrating the inherent safety of the coupled system.

1. INTRODUCTION

Nuclear power plants operate most efficiently at a constant power level and usually provide base load power to the electric grid [1][2]. However, the power demand profile always varies over day and night operating cycles. As a result, load–following is an important factor in power plant operation, especially when an electric grid includes highly variable renewable energy sources [1]. In an electric grid containing a large fraction of variable generation rate power sources, the load demands on the baseload energy sources such as nuclear power plants will be highly variable [1]. This will place significant stress on nuclear plants, as these systems are generally designed to operate at a constant power level. Additionally, variable power demands will result in a significant amount of curtailment, which is particularly disadvantageous to the economics of high capital cost power sources such as nuclear [1].

Coupling a nuclear reactor to large–scale thermal energy storage can significantly improve the viability of the nuclear power plant in an electricity grid containing a significant fraction of renewable energy sources. The nuclear reactor will operate at a constant power level, supplying heat to the thermal energy storage (TES) block. The TES block will provide heat as needed to the electric generation subsystem, which can be designed to rapidly respond to changes in electric power demand [1]. Thus, the nuclear reactor is allowed to operate at an optimal constant power level, buffered from changing demands by the TES block. Figure 1 illustrates the coupled Nuclear Reactor–Thermal Energy Storage (RX–TES) system considered in this paper. A 300 MW_{th} Prismatic–core Advanced High Temperature Reactor (PAHTR) provides power to a lithium chloride (LiCl) TES system. The LiCl TES system is coupled to a Closed Brayton Cycle (CBC) power conversion system which can rapidly respond to changes in electric load demand.

2. NUCLEAR REACTOR DESIGN

Figures 2 and 3 present axial and radial views, respectively, of the Prismatic-core Advanced High Temperature Reactor (PAHTR) shown in Figure 1. Table 1 presents the key design specifications of the PAHTR. The PAHTR design is based on previous designs such as the Gas Turbine–Modular Helium Reactor [3] and Pebble–Bed Modular Reactor [3]. The use of a molten salt coolant in the PAHTR allows for the high exit temperatures and power densities needed for efficient energy storage and power conversion [3].

The PAHTR core is prismatic with an aspect ratio of 1.31, containing 90 prismatic fuel assemblies (see Figure 3) with a total height of 525 cm. Each one of the assemblies consists of a 36 cm flat–to–flat graphite block containing 358 fuel rods, 216 coolant channels, 20 control rods, and a central handling tool (see Figure 4). The fuel rods in each prismatic fuel assembly contain Tri–Structural–Isotropic (TRISO) fuel particles in a graphite matrix with a packing factor of 35%. Figure 5 shows the TRISO fuel configuration used in the PAHTR. The central 19.75 wt% enriched UO_2 fuel kernel is surrounded by a porous carbon buffer layer [4]. An inner pyrolytic carbon (IPyC) layer surrounds the porous carbon layer and is coated with silicon carbide (SiC) [4]. Finally, the outer pyrolytic carbon (OPyC) layer protects the SiC layer [4]. The PAHTR contains ∼10 metric tons of uranium, which provides a five year operating cycle.

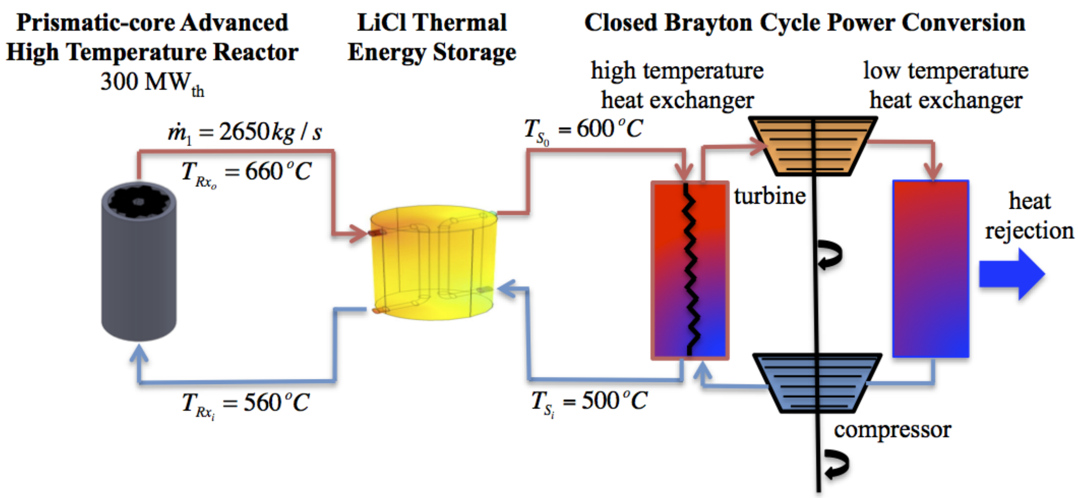


Figure 1: System block diagram for a coupled nuclear reactor–thermal energy storage system.

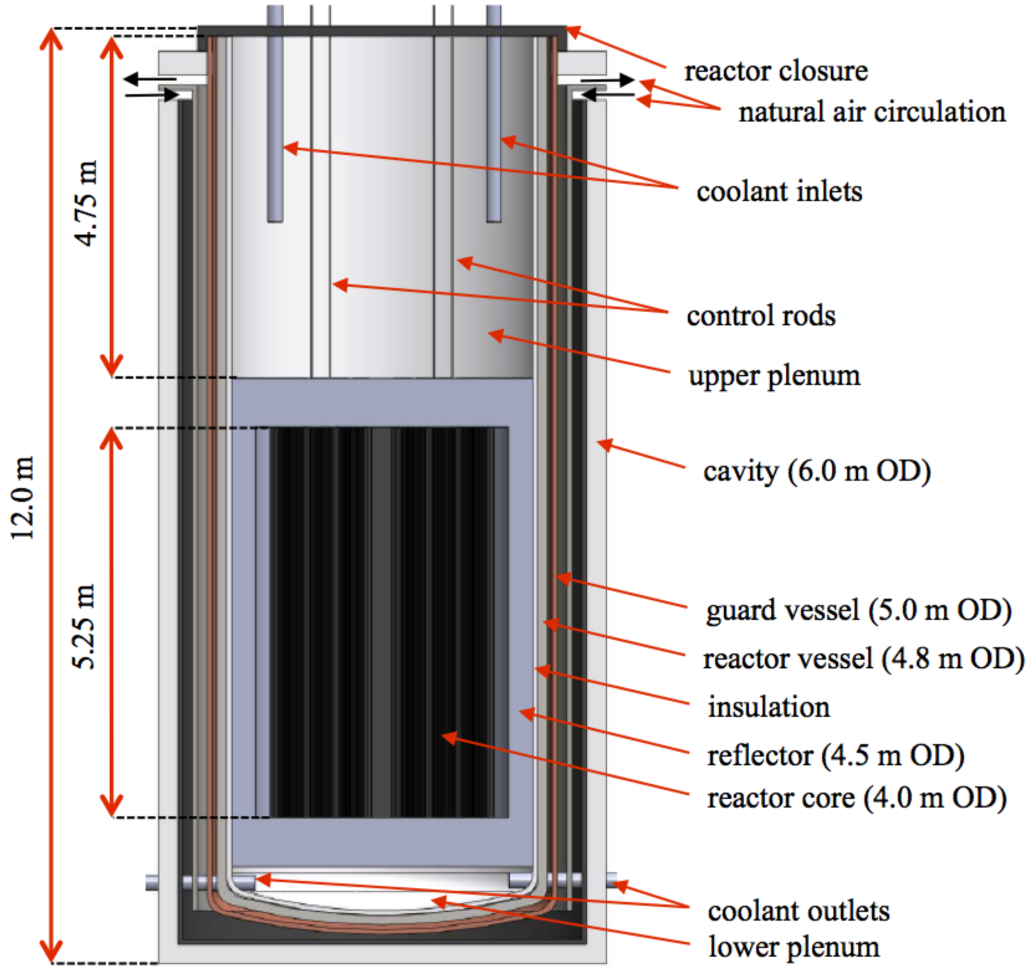


Figure 2: Axial cutaway view of the PAHTR.

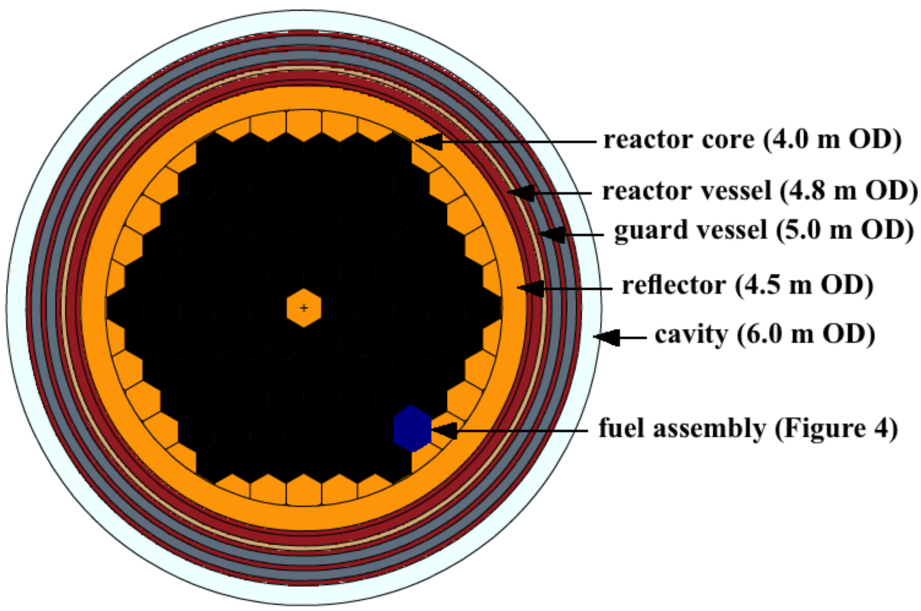


Figure 3: Radial cross section of the PAHTR core.

Table 1: PAHTR design specifications

Power	300 MW_{th}
Average power density	4.64 W/cc
Inlet temperature	560 °C
Outlet temperature	660 °C
Temperature differential	100 °C
Coolant flow direction	downward
Active core diameter	3.96 m
Active core height	5.25 m
Active core volume	64.66 m^3
Fuel assemblies	90
Fuel rods per assembly	358
Coolant channels per assembly	216
Fuel rod radius	0.6225 cm
Coolant channel radius	0.5 cm
Fuel type	TRISO (430 μm OD UO_2 kernel)
Packing factor	35%
Enrichment	19.75 wt% U–235
Heavy metal mass	∼10 MT

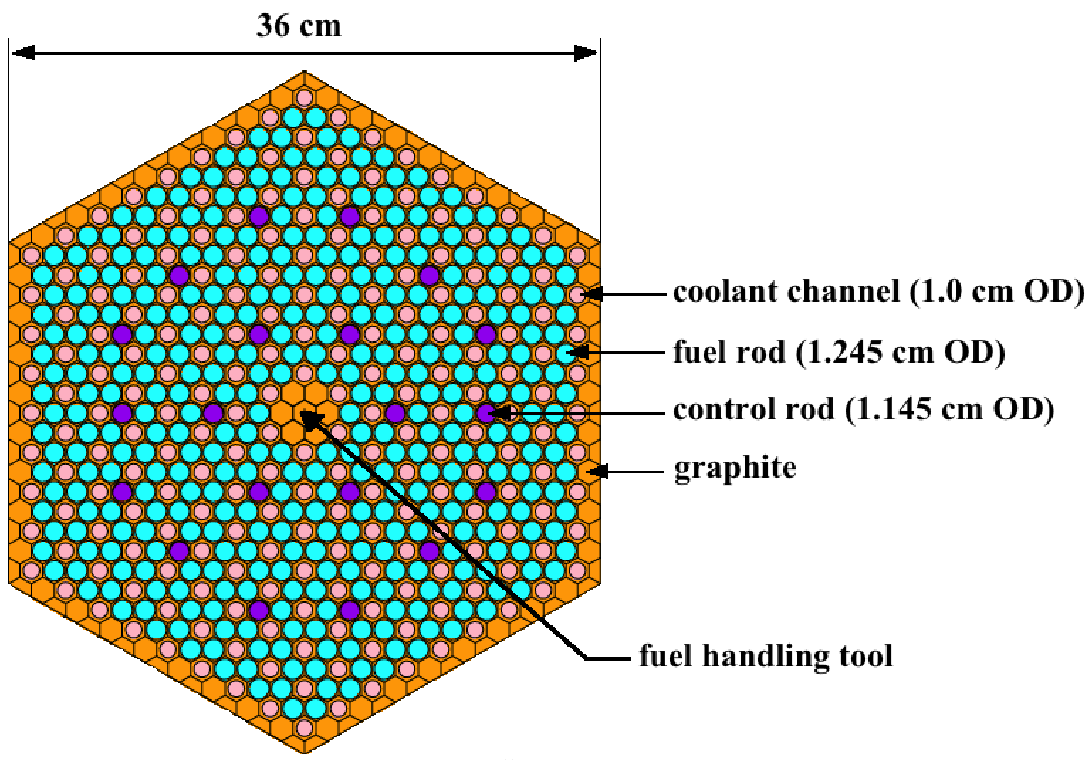


Figure 4: Radial cross section of a PAHTR fuel assembly.

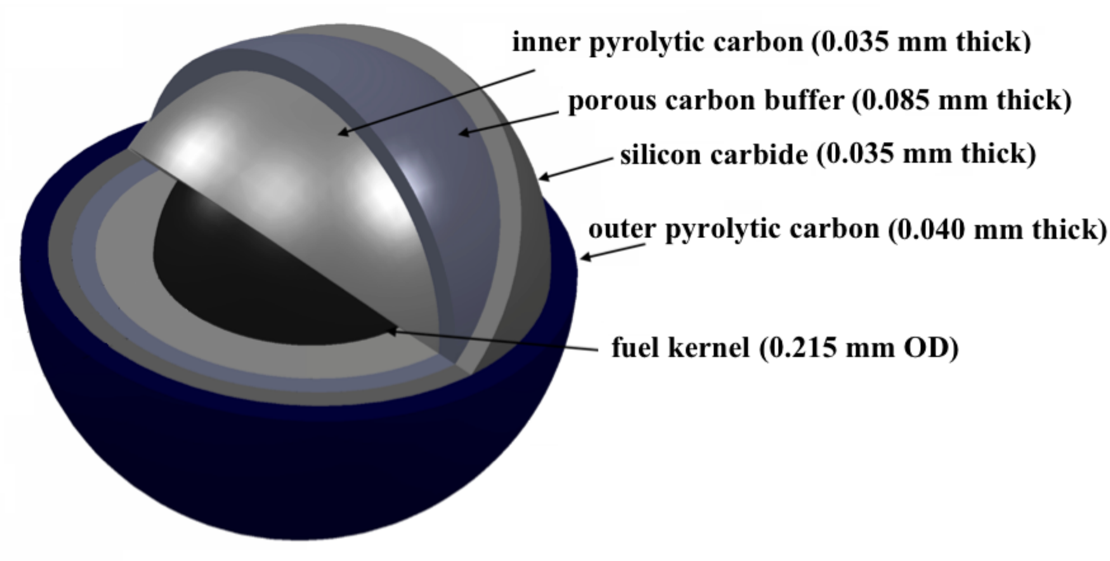


Figure 5: PAHTR TRISO fuel particle.

FLiBe (Li_2BeF_4) serves as the molten salt coolant in the PAHTR. FLiBe has very good compatibility with graphite fuel, a low melting point (459 °C), a high boiling point (1400 °C), and very favorable heat transfer properties [3]. In order to remove radioactive decay heat after an emergency shutdown, the PAHTR includes a passive Reactor Vessel Auxiliary Cooling system (RVAC) [5]. After shutdown, the heat from the reactor fuel will be transferred to the reactor vessel by the natural circulation of the liquid salt. Natural air circulation will remove the heat from the reactor vessel to the exterior of the reactor. As an additional safety measure, a guard vessel is added to the reactor facility (see Figures 2 and 3). In case of any failure of the primary vessel, the coolant will be contained by the guard vessel. The gap between the two vessels is filled with argon [5].

3. THERMAL ENERGY STORAGE DESIGN

Thermal energy storage (TES) blocks are usually considered in conjunction with concentrated solar power renewable energy sources [6]. A TES block takes the excess heat generated during peak power generation and stores it as thermal energy in the storing media [7]. Later, when energy production is low, the stored energy in the TES is discharged to the electricity production system [7].

There are two main mechanisms to store energy in an inert material, either as sensible heat or as latent heat [8]. Depending on the operating conditions of the TES block, energy storing materials will operate either in the latent or sensible heat region. As the temperature of a substance increases, the energy content also increases. Figure 6 shows the relationship between stored heat and temperature in the different regions.

During an unplanned shutdown, the TES block can take excess heat and store it or transfer it to a final heat–sink such as a cooling tower. Thus, the TES block can enhance the safety of the nuclear reactor as well as improving the operating characteristics of the PAHTR.

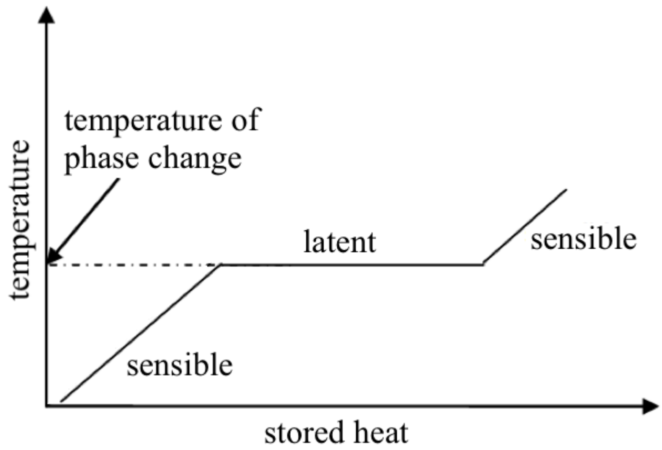


Figure 6: Sensible heat versus latent heat energy storage.

In any TES block, the choice of energy storing material will vary depending on the type of storing mechanism [8]. For sensible heat storage, either solid or liquid materials are used, with the selection of a specific material depending on the operating temperature. Examples of solid heat storage materials include concrete, rocks, and some types of ceramics [8]. Molten–salts or synthetic oils are usually chosen as liquid storage media [8].

For latent heat storage, a phase change material (PCM) stores heat as the heat of fusion, when the phase changes from solid to liquid (generally recommended), or as the heat of vaporization, when the phase changes from liquid to vapor [6]. Latent heat storage usually results in a smaller TES block, but can result in more complicated heat transfer and TES block design [8]. Table 2 details two different energy storing materials selected to store 150 MWd of thermal energy from the PAHTR: lithium chloride (LiCl) in the latent heat region and sodium chloride/magnesium chloride eutectic (NaCl–$MgCl_2$) in the sensible heat region [9]. In the PAHTR Rx–TES system, storing energy in the latent heat region results in a smaller TES volume, compared to sensible heat storage, by about a factor of four.

In the reminder of this project, lithium chloride is used as the phase change energy storage material. Lithium chloride has a high latent heat capacity of 416 kJ/kg, so this will store the necessary heat with a reasonable mass and volume for the TES block [10]. The TES block will be kept in the phase change region for lithium chloride, between the solid and liquid phases, which this will allow the maximum amount of heat to be stored with little change in the temperature of the material. This will also minimize the mass of the material required [11]. The amount of energy stored in this system is represented by Equation 1. If the thermal storage operates outside the latent heat region, Equation 2 describes the energy stored as sensible heat.

$$\Delta Q = \Delta H = m\Delta h \tag{1}$$

$$\Delta Q = mC_p\Delta T \tag{2}$$

Table 2: Comparison between potential latent and sensible heat storage materials

	LiCl	NaCl–$MgCl_2$
Total energy storage (MWd)	150	150
Melting temperature (°C)	610	450
Heat of fusion (kJ/kg)	416	430
Specific heat (J/kg.K)	1132	1000
Density (kg/m^3)	2070	2230
Total volume (m^3)	15050	58116
Total mass (kg)	$3.12\text{x}10^7$	$13.0\text{x}10^7$

4. TRANSIENT ANALYSIS

A transient simulation of the coupled nuclear reactor–thermal energy storage system demonstrates the potential benefits of proposed system. In this simulation, the thermal power generated by the nuclear reactor will either be stored in the latent heat TES block or passed to the electric generators through the heat exchangers in the TES block. The transient system simulation, described in the next subsection, consists of Simulink [12] models for the TES block and the reactor, including models for reactor fission power and decay heating.

4.1. Transient System Model Description

The transient system model contains Simulink modules for reactor kinetics, reactor thermal hydraulics, reactor decay heating and thermal storage modeling.

4.1.1. Reactor kinetics module

The six–delayed group point kinetics model simulates the transient behavior of the reactor in response to changes in external reactivity and temperature [13]. The delayed neutron fractions and decay constants are calculated by a SERPENT [14] model of the reactor. A MCNP [15] model of the reactor provides the prompt generation time. Table 3 lists the reactor kinetics parameters used in the reactor kinetics module.

4.1.2. Reactor thermal–hydraulics module

The reactor thermal–hydraulic module calculates the average core graphite, coolant, and fuel temperatures based on heat balance equations [13]. The average core graphite temperature is estimated based on the difference between the thermal power predicted by the reactor kinetics module and the heat removed from the graphite core material to the coolant. The average coolant temperature is calculated from the difference between the heat transferred from the core graphite material to the coolant and the heat taken out of the reactor by the coolant. The fuel temperature is determined by the spherical heat conduction equation. The temperature dependent thermal conductivity in each layer of the TRISO particle is approximated based on the average core graphite temperature.

Table 3: Reactor kinetics parameters used in the reactor kinetics module

Six–delayed group parameters		
Group	Delayed neutron fraction	Half–life (sec)
1	0.00021	55.494
2	0.00109	21.793
3	0.00106	6.333
4	0.00302	2.184
5	0.00089	0.512
6	0.00031	0.080
Prompt generation time (sec)		$1.6643\text{x}10^{-4}$

4.1.3. Reactor decay heat module

The decay heating module accurately tracks the decay heat produced by the reactor during operation and after shutdown. The decay heat is calculated using 23 delayed power groups for uranium–235 based on the 1979 ANS decay heat standard [16]. The decay heat is added to the instantaneous power predicted by the reactor kinetic module, as shown in Equation 3:

$$P_{eff} = P_{inst} + P_{decay} \tag{3}$$

4.1.4. Thermal energy storage module

The TES block is sized to store up to 150 MWd ($1.3\text{x}10^{13}$ J) of thermal energy as latent heat. The thermal energy storage module calculates the temperatures of the primary heat exchanger, secondary heat exchanger, and the energy storage material. The temperature of the thermal storage material operating in the latent heat region is constant at the melting temperature of the storage material (lithium chloride with a melting point of 610 °C). Above or below this operating region, the bulk storage temperature will vary as shown in Figure 6. To determine the operating region of the TES block, the liquid volume fraction is calculated and tracked as heat is accumulated or removed from the TES block. If the liquid volume fraction is between 0 and 1, the system is operating in the latent heat region; otherwise, if the liquid volume fraction is 0 or 1, the TES block is operating in the sensible heat region. The surface area of the primary and secondary piping of the thermal storage is assumed to be very large. Using this assumption, the thermal storage outlet temperatures will be equal to the bulk storage material temperature.

4.2. Transient Model Results

The simulation of normal operation over a 24-hour demand cycle verifies the stability of the coupled system. A Loss of Forced Circulation (LOFC) accident simulation demonstrates that decay heat can be removed to the TES block via natural circulation after shutdown.

4.2.1. Normal operation

For typical operation of the Rx–TES system, the TES block stores thermal energy during the night for use in the times of peak demand during the day. In this scenario, the nuclear reactor stays at a constant thermal power level. Figure 7 illustrates the reactor power output, the power demand from the TES bock and the liquid volume fraction in the TES block as a function of time. Starting at 9 pm, the TES block is storing energy as latent heat in the LiCl phase change material until 7 am in the morning. During the daytime, the demand will vary through different peaks that are above the constant power of the reactor. The reactor remains at a constant power level as the demand is met from the energy stored in the TES block. Figure 7 shows how the LiCl liquid volume fraction varies with the power demand, proportional to the stored energy. During normal operation, the reactor and thermal storage temperatures, and the thermal power of the reactor, are essentially constant.

In addition, around 40% of the thermal energy storage is kept as an energy reserve in case of an emergency. At the beginning of the cycle in Figure 7, the system contains 40% of the total thermal storage. This reserved energy (5.76×10^{12} J) will be enough to power emergency systems with power ratings of 120 MW_{th} for almost two weeks. This will eliminate the need for significant backup batteries in the Rx–TES plant.

4.2.2. Loss of forced circulation accident

In this scenario, the reactor operates at steady state with a thermal fission power of 300 MW_{th}. After five hours of operation, a loss of forced circulation is simulated by changing the mass flow rate in the primary loop to zero. At this point, the reactor coolant, graphite, and fuel temperatures begin to increase as shown in Figure 8(a). This increase in temperatures adds negative reactivity to the reactor core, reducing the effective

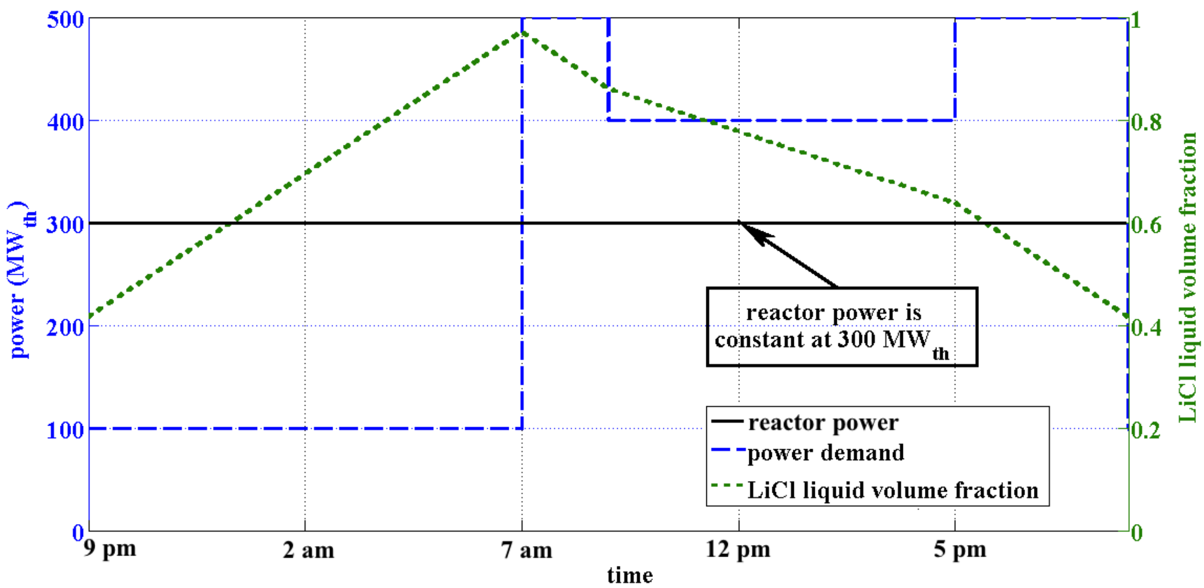


Figure 7: Normal operation of the coupled Rx–TES system.

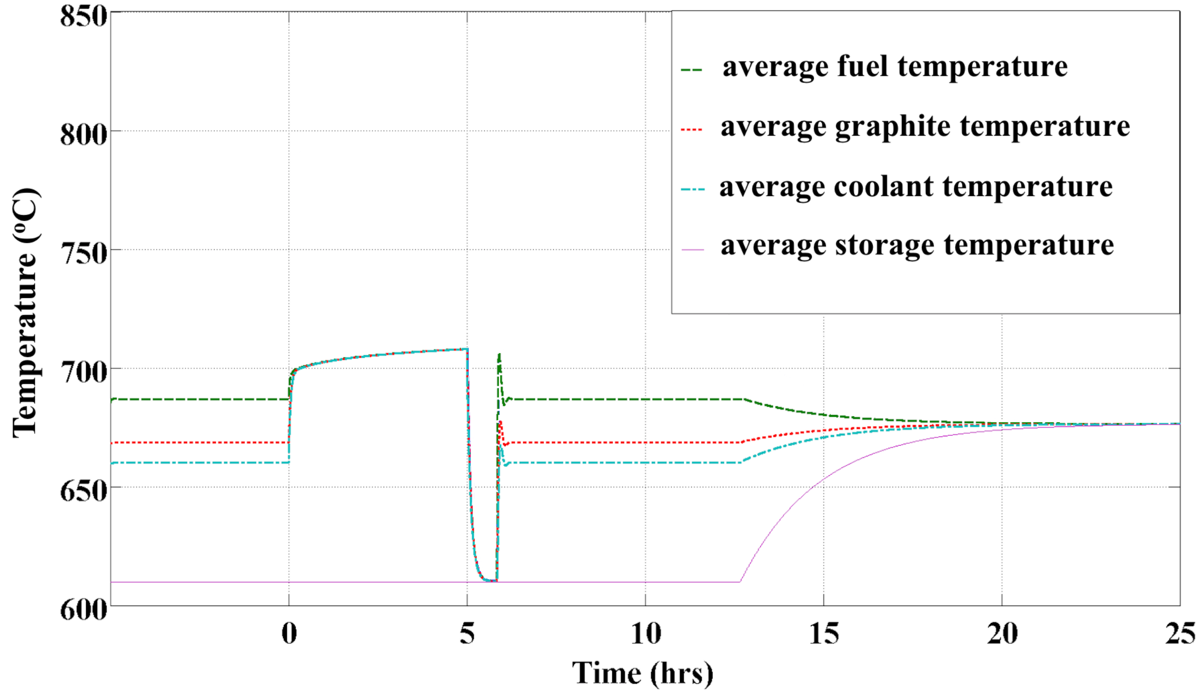
multiplication factor to less than one. As a result, the fission power drops exponentially, reaching a shutdown condition in less than half an hour (Figure 8(b)). Figure 8(a) shows that the maximum fuel temperature in this scenario is around 710 °C which is well within the safety limit for the TRISO fuel particles [4]. The TES block temperatures decrease with time as the reactor has stopped providing heat to the storage module.

Five hours after the loss of forced circulation, the primary coolant flow is restored to its previous level. This results in a rapid drop of the primary coolant temperature followed nearly instantly by a drop in the graphite and fuel temperatures. Assuming that a control system has not activated to ensure shutdown, this leads to a spike in the thermal fission power of the reactor (see Figure 8(b)). The reactor then stabilizes at a steady state condition. At this point, the thermal storage is not connected to any demand power and the system stores energy in the TES block as a latent heat, as the lithium chloride melts. The system temperatures will remain constant while the TES block operates in the latent heat region. After about seven hours, all of the lithium chloride in the TES block has melted and the storage temperature starts to increase (Figure 8(a)). As a result, the inlet reactor temperature increases and the reactor power decreases (Figure 8(b)) until the inlet and outlet temperatures of the reactor reach equilibrium (Figure 8(a)). At this point the reactor has reached a passive shutdown state. Throughout this transient, the average temperatures in the reactor are all within safety limits, demonstrating the inherent safety of the system.

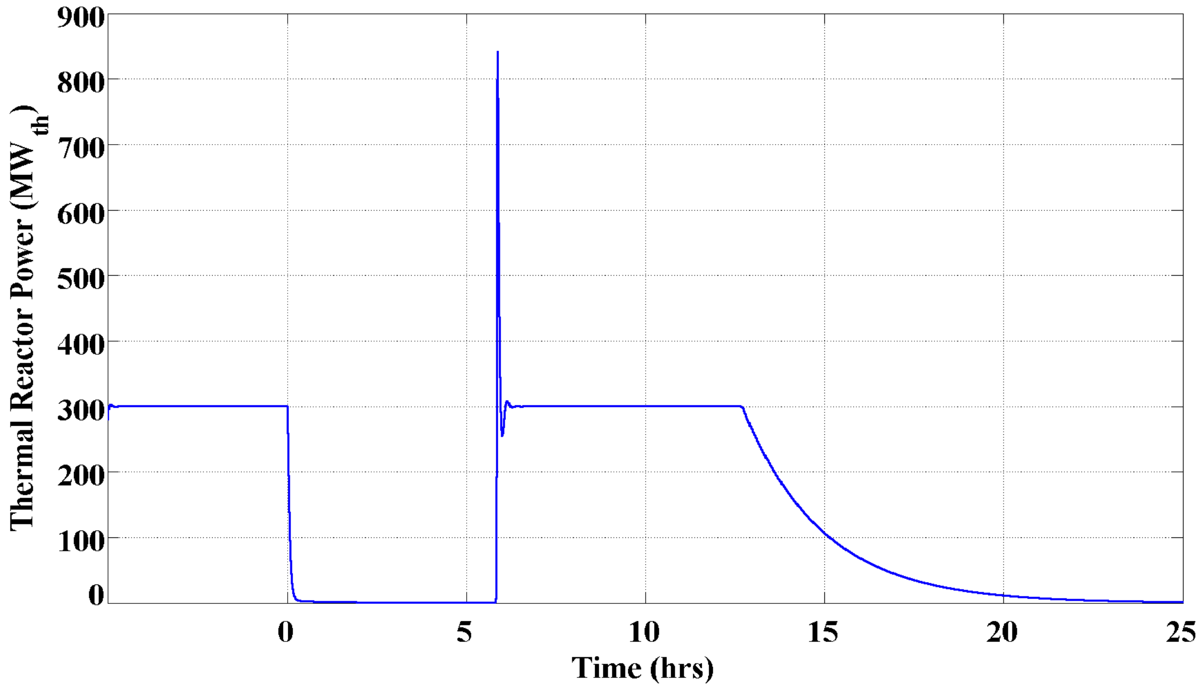
5. SUMMARY AND CONCLUSIONS

A Prismatic-core Advanced High Temperature Reactor (PAHTR) that uses TRISO particle fuel is designed to have a five year operating cycle with FLiBe molten salt as its primary coolant. The PAHTR is coupled with a lithium chloride–based thermal energy storage (TES) block that operates in the latent heat region with the capability to store 150 MWd of thermal energy. Kinetics, thermal–hydraulics, and decay heat models for the reactor are implemented in Simulink along with a thermal energy storage model.

Coupling the nuclear reactor to a thermal energy storage block enhances the load following characteristics of the nuclear reactor as well as providing additional safety margin in the case of an unplanned shutdown. During normal operation, the TES block stores thermal energy during the night for use in the times of peak demand during the day. In this case, the nuclear reactor stays at a constant thermal power level. Simulating a loss of forced circulation accident in the coupled Rx–TES system, demonstrates the inherent safety of the system. After a loss of forced circulation, the PAHTR reaches a shutdown state in less than half an hour. The average fuel, graphite and coolant temperatures remain within safety limits for the duration of the transient.



(a) Temperature transients.



(b) Thermal power transients.

Figure 8: Loss of forced circulation accident.

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