PASSIVE DECAY HEAT REMOVAL SYSTEM DESIGN FOR THE INTEGRAL INHERENT SAFETY LIGHT WATER REACTOR (I^2S-LWR)

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ABSTRACT

The Integral, Inherently Safe Light Water Reactor (I^2S-LWR) is an innovative pressurized water reactor (PWR) concept being developed by a multi-institutional team led by Georgia Tech and in collaboration with Westinghouse, under the Department of Energy's Nuclear Energy University Programs Integrated Research Projects (DOE NEUP IRP). The I^2S-LWR features an integral primary system configuration and is more conducive to the implementation of inherent safety features by eliminating potential accidents. In this paper, a novel passive Decay Heat Removal System (DHRS), is presented, consisting of a primary loop, an intermediate loop and a cooling tower loop. This passive system is designed to remove the I^2S-LWR decay heat in the case of emergency heat removal transients, without the need for external power or operator action. The proposed DHR uses atmosphere as ultimate heat sink, to achieve indefinite decay heat removal. In this paper, firstly, the design of primary and secondary DHRS heat exchangers is optimized. Then the DHR heat removal characteristics are studied using the best-estimate thermal hydraulic code RELAP5. The performance of the DHRS concept is investigated in case of Station Black-Out accident. Results show that three of the four DHRS trains are sufficient to indefinitely remove the core decay heat successfully, and keep the reactor in a safe state without the need of any other auxiliary active system.

KEYWORDS
DHR, Integral reactor, Station Black-Out, Heat removal

1. INTRODUCTION

The Integral, Inherently Safe Light Water Reactor (I^{2}S-LWR) is a novel reactor concept being developed by a multi-institutional team, under the Department of Energy's (DOE) Nuclear Energy University Programs (NEUP) Integrated Research Projects (IRP), aiming to implement some inherent safety features by eliminating potential accident initiators [1]. The I^{2}S-LWR builds on other integral reactor designs, such as the International Reactor Innovative and Secure (IRIS) [2] and the Westinghouse Small Modular Reactor (W-SMR) [3], and it incorporates novel features to allow for much higher power outputs (in the range of 1000 MWe) while still featuring an integral configuration.

Several significant innovative design concepts are applied to the I^{2}S-LWR. Passive safety system is one of the most safety characteristics of the I^{2}S-LWR and the target design will be able to remove decay heat indefinitely, by natural circulation, without the need for either an external power supply or replenishment of coolant supply, since ambient air will be the ultimate heat sink. Moreover, a novel approach to instrumentation and monitoring will ensure that plant status is reliably known in normal, off-normal, and especially post-accident conditions. Finally, the whole nuclear island will be seismically isolated to guarantee its protection against earthquakes with magnitude within the historical record, and to limit the consequences of stronger earthquakes. The enabling innovation is the use of high power density technologies/components in synergy with an integral configuration. A compact core design is achieved by using a non-oxide fuel form with improved heat removal capability, combined with fuel/clad design of enhanced accident tolerance. This allows increasing core power density while at the same time improving the core safety performance and response in transient/accident scenarios. The novel steam generating system is based on very compact Primary micro Channel Heat Exchanger (PCHE) in combination with flashing drums [4], which makes a 1,000 MWe power level compatible with an integral configuration.

In addition to the systems and components contained in the Reactor Pressure Vessel (RPV) of typical, non-integral designs, the I^{2}S-LWR pressure vessel includes control rod drive mechanisms (CRDM), the pressurizer, the primary heat exchangers and the decay heat removal system (DHRS) heat exchangers. Figure 1 shows the I^{2}S-LWR RPV and the internals layout.

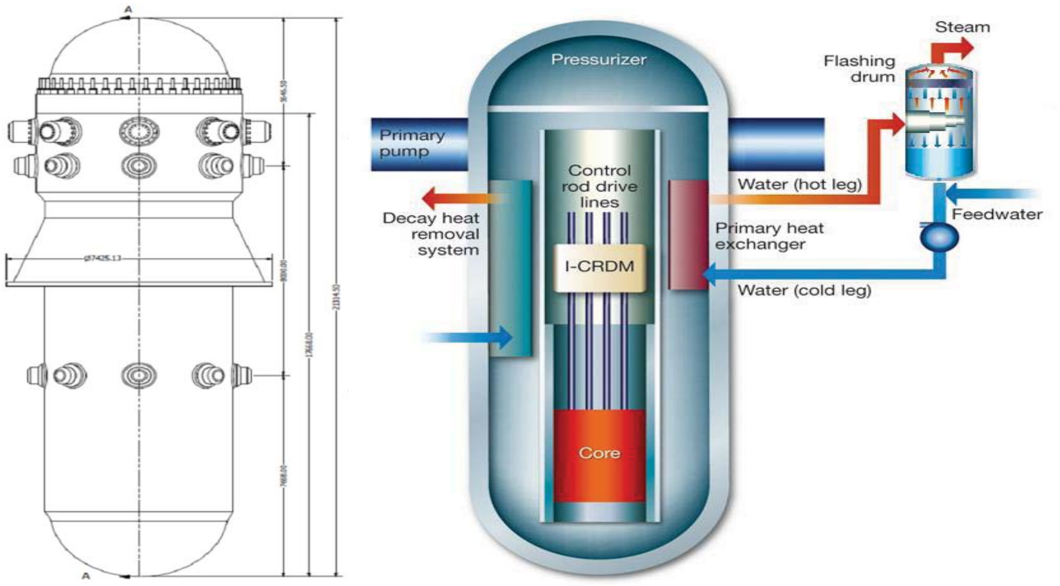


Figure 1. I2S-LWR configuration [5]

Passive safety is fundamental concept proposed several years ago for the new nuclear power plant (NPP) design. It can remove reactor core decay heat by natural circulation and improve the NPP safety level in case of emergency conditions. In the passive concept, primary safety functions, including both accident prevention and mitigation, are provided in direct and simple ways, relying primarily on forces as gravity injection and natural circulation. Early studies concluded that passive safety systems are technically and economically applicable to small and midsize NPPs, and that they can be applied to both Boiling Water Reactor (BWR) and pressurized water reactor (PWR) technologies [6]. In recent years, research has been focused on the application of passive safety systems in large power LWRs [7]. For example, the AP1000 design developed by Westinghouse has adopted an extensive use of passive systems to improve the NPP safety, relying on gravity, compressed gas, natural circulation, and evaporation for long term reactor cooling in accidental events [8]. A station blackout accident simulation for a typical PWR where high and medium pressure injection pumps were replaced by passive injection components was performed using RELAP5 code, in order to analyze the degree of plant safety (without any operator action) by using only the passive components [9]. Research on heat removal by in-pool immersed heat exchangers was performed at SIET laboratories using the PERSEO facility by experimental method [10].

Learning from past experience, with the I^{2}S-LWR design we propose to further increase LWRs safety beyond that of Gen-III+ and toward inherent safety by:

- Eliminating accident initiators as far as achievable: in the I2S-LWR, large and intermediate break Loss Of Coolant Accidents (LOCA) are eliminated by design. The only potential LOCA scenarios include small break LOCA as a consequence of a stuck-open PORV, and the break of a Control Volume System (CVS) pipeline. There may also be the potential for small (1") breaks of service lines (such as cooling of pump motors if seal-less pumps with external heat exchangers are used, etc);
- Limiting the loss of inventory during LOCA scenarios: the I2S-LWR design feature a high pressure containment. Loss of inventory is limited by a set of systems which allow to quickly reach pressure equilibrium between RPV and containment;
- Increasing the level of passivity of all foreseen safety systems to the IAEA passivity level C [11] and above, limiting the use of components which require moving parts.

By eliminating both intermediate and large-break LOCAs scenarios, by limiting the loss of inventory during SBLOCAs and by foreseeing passive safety features which do not rely on stored energy (batteries, etc.), a long-term (theoretically unlimited) self-sustained decay heat removal capability with no need for intervention in case of an accident and loss of external power can be achieved.

The safety philosophy of the I^{2}S-LWR design is based on three consecutive lines of defense:

- The first and main line of defense is aimed at preventing core damage, especially in the event of a prolonged loss of offsite power. This is pursued by eliminating event precursors as far as achievable, by limiting the loss of RPV inventory in case of LOCAs, and by designing safety systems with a very high degree of passivity;
- The second line of defense is aimed at cooling the containment vessel by air or other medium in natural circulation regime;
- The third line of defense is aimed at protecting the Containment Vessel (CV) from external events. This is accomplished by partially burying the CV, so that the risk of a plane crash can be reduced, and by placing the CV on seismic isolators to mitigate the effect of earthquakes. The safety systems are designed with level of passivity C, so that even in the event of a flood the reactor will not suffer any damage.

The passive safety systems foreseen for the containment cooling are illustrated in a companion paper [12], where their performance is demonstrated against a stuck-open Pilot-operated Relieve Valve (PORV) event. The present paper is instead focused on the DHR system, designed to remove the decay heat from the primary loop, using external atmosphere as the ultimate heat sink.

The DHR system proposed in the present paper for the I^{2}S-LWR consists of four independent trains. Each train includes a helical coil HX located in the RPV, an intermediate loop and a cooling tower system. The DHRS is designed to remove reactor core decay heat in case of loss of the secondary side heat sink, maintaining the reactor in a safe state.

In the following section, the detailed design of the DHRS is presented. A Relap5 model of the I^{2}S-LWR primary loop and DHRS is then employed to investigate the DHRS heat removal characteristics in the event of a Station Black-Out (SBO) transient.

2. DHR DESIGN FOR THE I^{2}S-LWR

The passive DHR is the main safety related system foreseen for the I^{2}S-LWR [13] to bring the reactor to a safe-shut-down state without the need for any operator action. In our design, the DHR system comprises of four trains, each consisting of two heat exchangers, a fail-open valve, and the required piping between these components. A single train is illustrated in Figure 2. There are two thermally coupled loops (hydraulically isolated) that transfer heat from the reactor to the environment. The helical coil design was chosen for the primary heat exchanger because it provides high heat transfer capability in a limited space, while maintaining low pressure drops, important to guarantee a sufficient degree of natural circulation. The outlet leg of the helical coils is placed in the downcomer, at an elevation close to the core inlet, while the inlet leg is placed in the downcomer, just below the elevation of the top of the core. An intermediate loop, operated with pressurized water, is used to transfer heat from the primary heat exchanger to a dry cooling tower, where atmosphere is used as the ultimate heat sink.

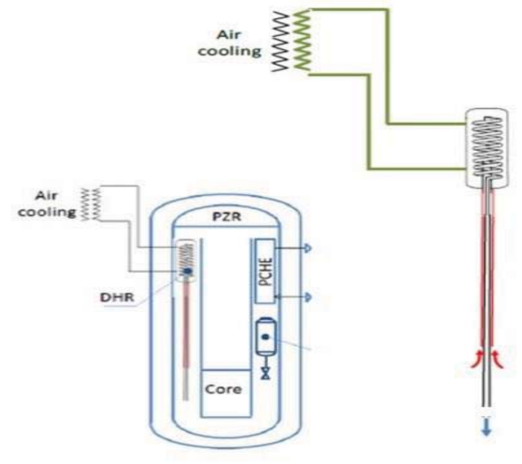


Figure 2. Illustration of DHRS Concept, Including Arrangement in Reactor Vessel

As alternative designs we have considered:

- Inlet leg of the primary DHR helicoidal heat exchanger placed at the exit of the core. While this would allow for higher natural circulation in the DHR because of the higher temperature gradient between inlet and outlet legs of the HX, it also involves additional design challenges as the DHR inlet leg would have to be accommodated in the RPV upper plenum where control rod drive mechanisms and other internals are present;

- Molten salt or nanofluids as operating fluid for the intermediate DHR loop. Molten salts would enable natural circulation without employing long vertical pipe sections, which are otherwise needed when water is used instead. Molten salt however add the challenge of salt solidification, which needs to be prevented at all times. The use of water with nanofluids has the advantage of enhanced heat transfer. Still, long vertical pipe sections of the intermediate loop including loop pressurization would be needed in this case.

Currently, the above alternatives have not been included in the final design, as our preliminary analyses reported in the next chapter have shown that the main DHRS design performs adequately.

2.1 Helical Coil HX Design

The primary DHR heat exchanger consists of a helical coil design optimized for natural circulation flow. These exchangers were pioneered with the Otto Hahn reactor, and are known for their low hydraulic resistances, high surface area, and low mechanical and thermal stresses. They are currently proposed by NuScale for their natural circulation reactor. These tubes are held in place by vertical baffles with alternating holes, as illustrated in Fig.3 [14]. In our present design, the primary coolant flows inside the helical coils, while the shell side of the HX is part of the intermediate loop. In order to achieve consistent flow conditions, the geometry of the helical coil tubes are varied to create near uniform internal and external flow and heat transfer characteristics. A MATLAB script is used to optimize all the helical coil HX parameters [13]. The basic design parameters are summarized in Table Ⅰ.

Table Ⅰ Main parameters of helical coil HX

Parameters	Meaning	Designed value
L	Height of heat exchanger	8.01 m
Di	Outer shell inner wall diameter	0.694 m
Do	Inner shell outer wall diameter	0.11 m
do	Tube outer diameter	0.013 m
di	Tube inner diameter	0.0111 m
P	Axial pitch	0.0286 m
Ddownc	Down-comer primary side DHR	0.0737 m
Ncoils	Number of coils	9
t	Radial pitch	0.03435 m
Φ	Average inclination angle	-12.4462°

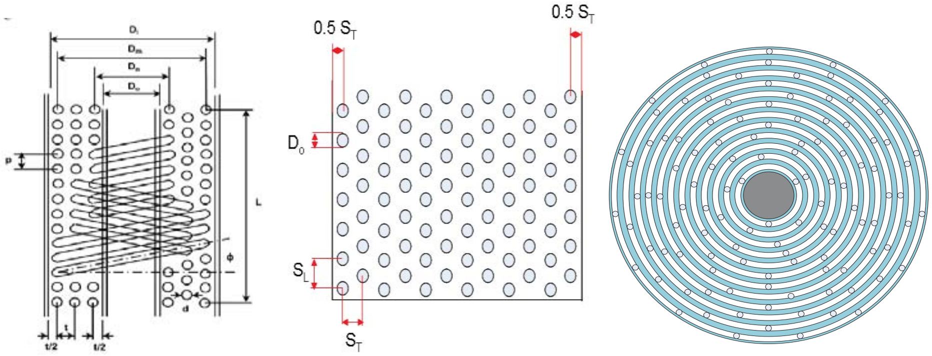


Figure 3. DHRs primary helical coil HX configuration

2.2 Cooling Tower Design

The second DHR exchanger is a water-air exchanger located within a dry cooling tower, and is used to transfer heat from the intermediate loop to air in the environment. The general cooling tower shape is a hyperboloid. The hyperboloidal shape allows for a better air flow distribution and helps reducing the wind impact on the structure [15, 16]. Generally, the shape of a hyperboloidal cooling tower shell consists of a lower and an upper hyperbola branch, which both meet at the throat (see figure 4). The hyperbola axis does not need to correspond with the tower axis. Thus the curvature of the meridian varies over the tower height, in general with a maximum at the throat [17].

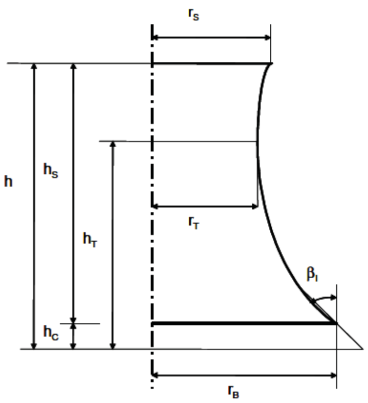
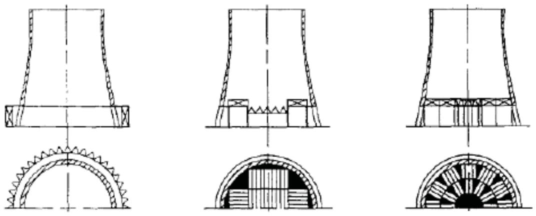


Figure 4. Cooling tower geometric diagram

The heat exchanger tube arrangement is another important factor that needs to be considered carefully. In most practical towers the heat exchanger bundles are arranged either vertically around the circumference of the tower or horizontally at the inlet cross section (see figure 5). There are two possible arrangements for the horizontal configuration: rectangular and radial (see Figure 5 b and c respectively). For each of these only a part of the available cross section is occupied with heat exchanger tubes.



(a) (b) (c)

Figure 5. Heat exchanger bundles arrangements: (a) Vertical circumferential; (b) Horizontal rectangular; (c) Horizontal radial.

Based on the results on full scale measurements Moore [18] concluded that the heat transfer performance of the internal horizontal arrangement is less susceptible to wind variations than the external vertical one. In windless condition the heat rejection rate of a cooling tower is instead independent of the particular horizontal arrangement, for a given total heat exchanger surface area.

The total tower height h, column height h_C and base shell radius r_B are generally fixed by the thermal design, likewise the throat radius r_T with small admissible variability. The superior shell radius r_S must be not smaller than r_T to avoid flow perturbation. All other parameters can be freely selected within certain design limits. However, the geometrical parameters are in typical proportions between them [19], in order to optimize construction and architectural points of view. The inferior angle β of the shell inclination is restricted by:

$$\tan \beta_I \geq (r_B - r_T)/(h_T - h_C) \tag{1}$$

The other parameter constraints are shown in the following equations [20]:

$$\frac{(2\times r_B)}{h} = 0.75 \tag{2}$$

$$\frac{r_T}{r_B} = 0.55 \tag{3}$$

$$\frac{h_C}{(2\times r_B)} = 0.75 \tag{4}$$

$$r_S \geq r_T \tag{5}$$

$$L = r_B/\sqrt{5} \tag{6}$$

All the main parameters of cooling tower are shown in Table Ⅱ and the figure 4 shows the corresponding signs used in above equations. The sign of equality herein designates the smallest possible value of β_I, at which limit condition two conical frusta meet at the throat in a break point of infinite curvature. The maximum angle β_I is limited by the maximum possible inclination of the form-work system for the shell construction, by experience noticeable below 20°. It is an interesting fact that most of the above mentioned technical aspects improve for larger β_I, except for the aesthetics of the structure: a cooling tower generally is perceived as more pleasant for medium values of β_I.

Table Ⅱ Main parameters of cooling tower

Parameters	Meaning	Designed value
h	Total tower height	20 – 40 m
$\mathbf{r_e}$	Tube radius	0.0125 m
$\mathbf{r_B}$	Base shell radius	11.25 m
$\mathbf{r_T}$	Tower throat radius	6.19 m
$\mathbf{h_c}$	Base shell height	2.25 m
$\mathbf{h_t}$	Tower throat height	26.07 m
$\mathbf{r_S}$	Superior shell radius	6.19 m
$\mathbf{N_r}$	Axial tubes raw number per HX	96
$\mathbf{N_{total}}$	Total tubes number per HX	38592

2.3 DHR Heat Removal Characteristic Study

The performance of the DHRS helical coil loop and dry cooling tower is investigated in this section using the RELAP5 best-estimate thermal-hydraulic code. Relevant DHR operational parameters used in this study are listed in Table Ⅲ.

Table Ⅲ DHRs Operational Parameters

DHRS operation parameters	value
Primary Inlet Temperature (K)	597.04
Primary Outlet Temperature (K)	576.21
Water Inlet Pressure (MPa)	15.51
Intermediate Loop Temperature (K)	322.04
Intermediate Loop Pressure (MPa)	6.89
Cooling Tower Temperature (K)	283.15 - 323.15
Cooling Tower Pressure (MPa)	0.1

There are two primary challenges to the utilization of this particular passive DHRS: the first is ensuring sufficient heat transfer in the air/water heat exchanger. The second is ensuring that natural circulation flow is sufficient to remove decay heat prior to a significant buildup of energy within the reactor pressure vessel. Preliminary scoping studies have been performed to determine the potential performance of such a system and the analysis matrix is shown in Table Ⅳ.

Table Ⅳ Analysis Matrix

Parameters	value
Cooling tower height (m)	20, 25, 30, 35,40
Cooling tower inlet air temperature (K)	283.15, 288.15, 293.15, 298.15, 303.15, 308.15, 313.15, 323.15
Intermediate loop height difference (m)	5.24, 10.24, 15.24, 17.74, 20.24, 22.74, 25.24
Intermediate loop pipe diameter (m)	0.1, 0.2, 0.3, 0.4, 0.5

Preliminary sensitivity studies were undertaken to determine the design envelope for the various components within the DHR. The constant boundary conditions are assumed to study DHR heat removal characteristic. The DHR inlet coolant temperature is 597.039 K, while the outlet coolant temperature is 567.206 K. The DHR primary pressure is about 15.5 MPa, which is corresponding with I^2S-LWR vessel pressure. The DHR intermediate loop pressure is about 6.9 MPa and the cooling tower pressure is the atmosphere pressure 0.1 MPa. The DHR sensitivity study results are shown in Figure 6 to Figure 10. Figure 6 shows the heat removal capability of the DHR system for different cooling tower heights. The DHRS heat removal performance increases with increasing cooling tower height. However, significant increase of the heat removal performance is observed for cooling tower heights below 30 m. Increasing the tower height above 30 m yields only a moderate increase of the DHRS heat removal capacity. Given the cost of construction, a 30 m high cooling tower is deemed optimal. The cooling tower air mass flow rate is shown in Figure 7; it increases with tower height due to the increased buoyancy driving force. The DHR heat removal capacity for different atmosphere air temperature is shown in Figure 8. Clearly, a certain variability exists in the DHRS performance depending on the atmosphere temperature. An air temperature of 288.15 K is used for further calculations. Figure 9 and Figure 10 show the DHR heat removal characteristics influenced by the intermediate loop height difference and the intermediate loop pipe diameter. As expected, the mass flow rates in the intermediate loop increase with the height difference and the pipe diameter.

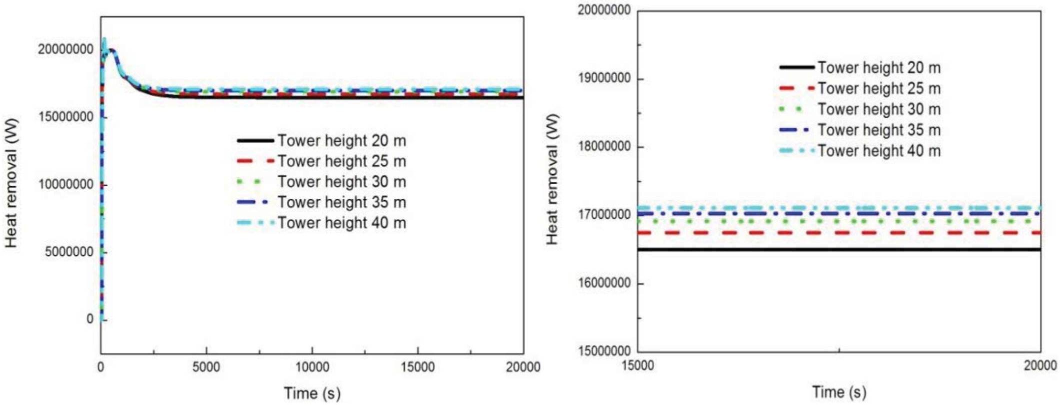


Figure 6. Decay Heat Removal of Each DHRS Loop as a Function of Cooling tower height

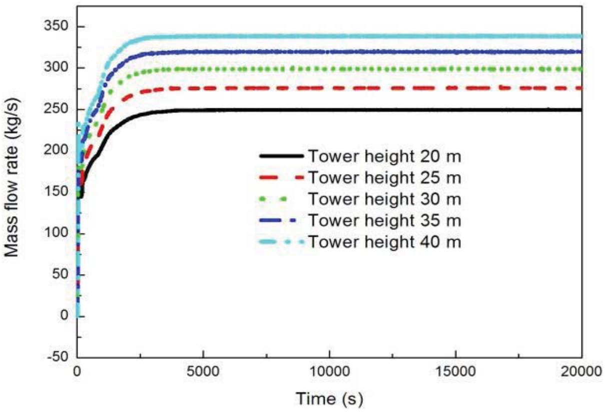


Figure 7. Cooling tower air mass flow rate as a Function of Cooling tower height

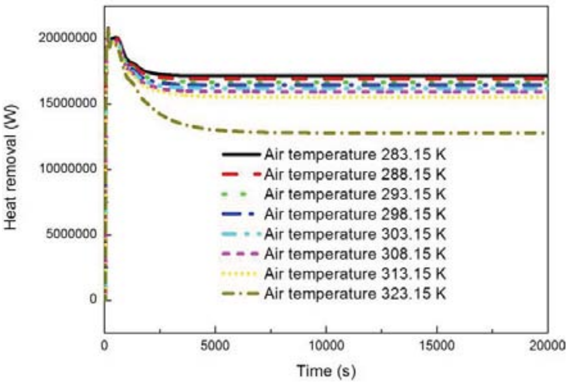


Figure 8. Decay Heat Removal of Each DHRS Loop as a Function of atmosphere temperature

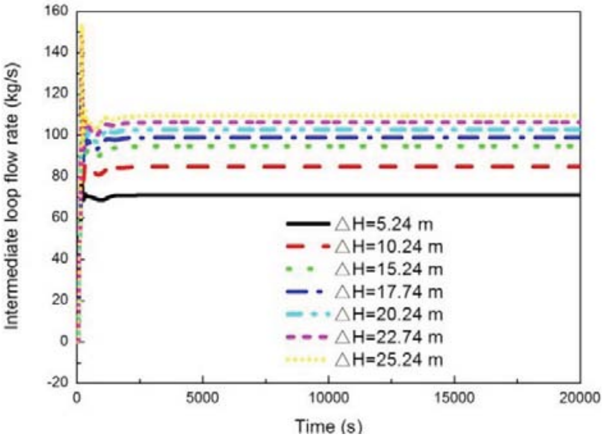


Figure 9 Intermediate loop mass flow rate as a Function of intermediate loop height difference

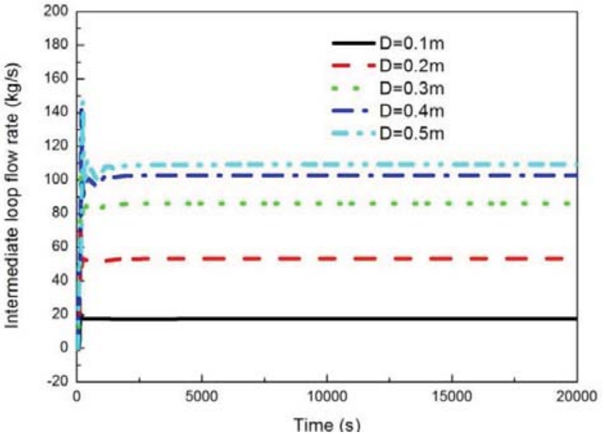


Figure 10. Intermediate loop mass flow rate as a Function of intermediate pipe diameter

In conclusion, as shown in the standalone DHR performance study [10], stable natural circulation is established in all three loops of the DHR system (primary, intermediate and dry cooling tower) and heat can be removed from the primary loop to the atmosphere successfully and indefinitely. In the next section the performance of the DHRS is investigated in the event of a SBO accident.

3. I^{2}S-LWR MODELING

The I^{2}S-LWR primary loop has been modeled using the RELAP5 best-estimate thermal-hydraulic code. In the RELAP5 nodalization, the I^{2}S-LWR RPV is divided into four identical sections, each including a reactor coolant pump component, a PCHE component and a downcomer section. The reactor coolant pumps are located between the pressurizer (at the top of the RPV) and the PCHE.

A diagram of the RELAP 5 nodalization for the I^{2}S-LWR primary loop and DHRS is illustrated in Figure 11. The reactor downcomer is divided into four parts and each part contains a PCHE component and a corresponding DHRS train. In the RELAP5 model, the reactor vessel, core, pressurizer, reactor coolant pumps, PCHE and DHRS are modeled in detail. Some auxiliary systems needed for the simulations are modeled using Time Dependent Volumes (TMDPVOLs) and Time Dependent Junctions (TMDPJUNs).

4. RESULTS AND ANALYSIS

4.1 Steady State Calculation

A steady state calculation was performed with the I^{2}S-LWR RELAP5 nodalization and the obtained results have been compared with the design parameters, as reported in Table Ⅴ. The reactor thermal power is 2850 MW, and the equivalent PCHE secondary side flow rate is set to 3128.25 kg/s per PCHE, based on an optimization study on the efficiency of the I^{2}S-LWR thermodynamic cycle [4].

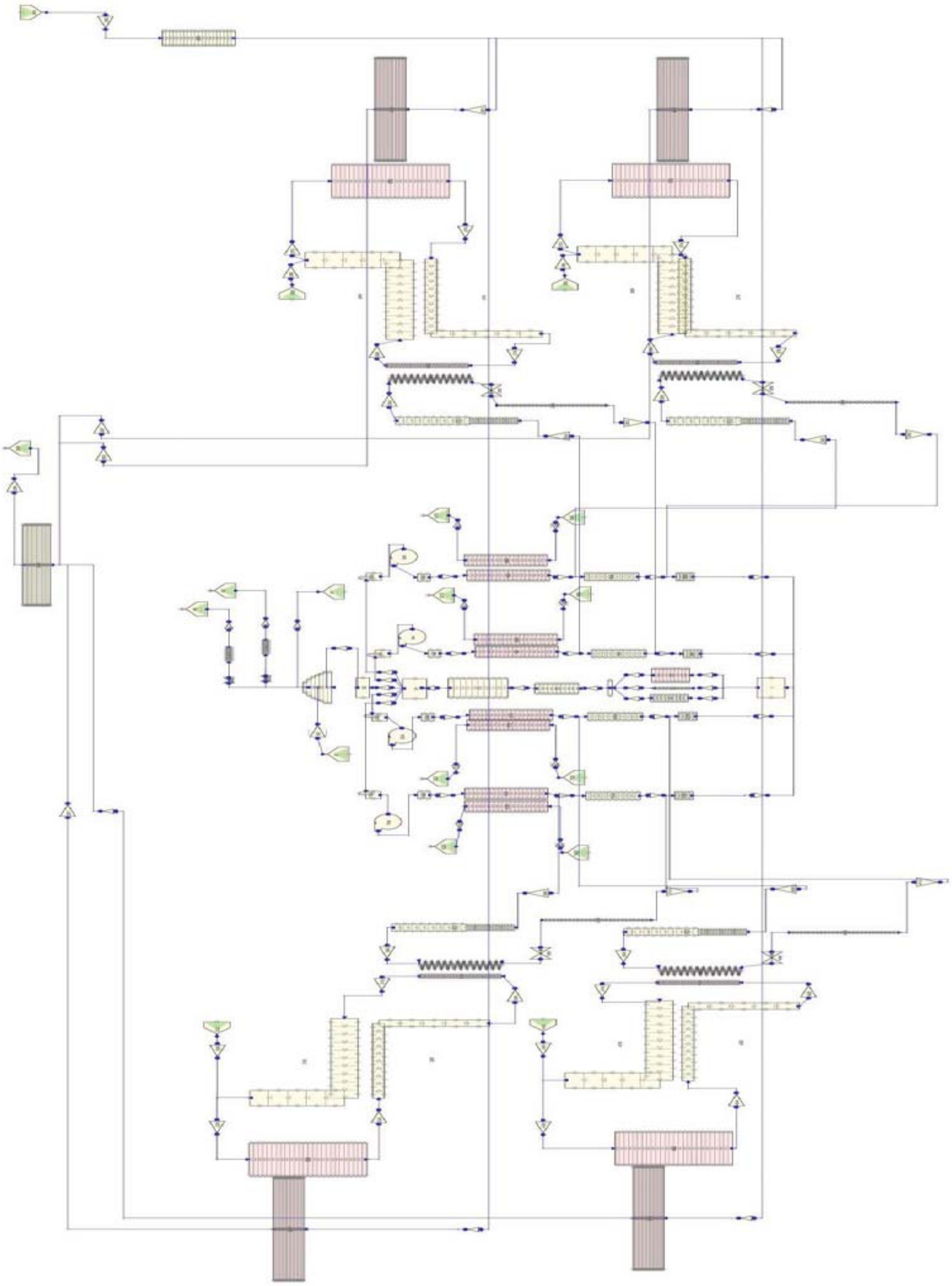


Figure 11. I2S-LWR and DHRs Relap5 Nodalization

Table Ⅴ Steady state results and comparison with designed value

Parameters	Designed value	Calculated value	Errors
Core inlet temperature (K)	571.15	567.60	0.45%
Core outlet temperature (K)	602.15	600.49	0.75%
Reactor pressure (MPa)	15.5	15.49	0.006%
Core flow rate (kg/s)	15467	15467.1	0.0%
Pressurizer water level (m)	3.24	3.24	0.0%

As shown in table V, the RELAP5 steady state results are in good agreement with the design parameters. In the next section, the Realp5 nodalization is used to simulate a SBO transient with three DHR system in operation.

4.2 SBO Transient Study

Starting from steady-state conditions at nominal operation, the SBO accident is assumed to occur at 0 s. The primary circuit pumps begin to coast down because of loss of power. The PCHE secondary feed water is assumed to decrease to 0 kg/s within 200 s. In order to be conservative, no credit is taken for the PCHE heat removal after the first 200 s of transient. Also, no credit is taken for any diesel generator. The DHRS valves, located in the intermediate loop, open upon receipt of the reactor shutdown signal, assuming 5 s delay of signal transfer. The accident logic for the SBO event is listed in Table Ⅵ. The reactor decay heat curve from Todreas/Kazimi [21] is shown in Figure 12. In this paper, three out of four DHRS trains are assumed to start operation.

Table Ⅵ Event sequence of SBO

Event	Time (s)
SBO occurs	0.0
Reactor shutdown trip	0.0
Secondary side flow rate trip	0.0 (200 s decrease to 0)
Pump run out trip	0.0 (Coast down time 250 s)
DHR valve open trip	5.0

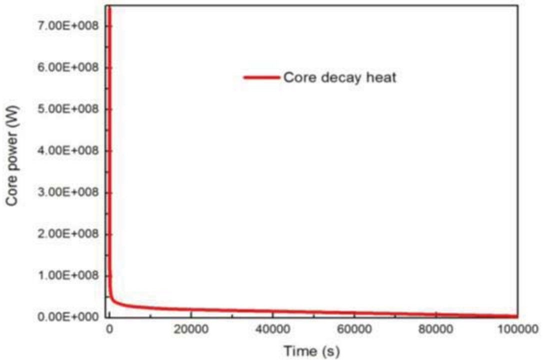
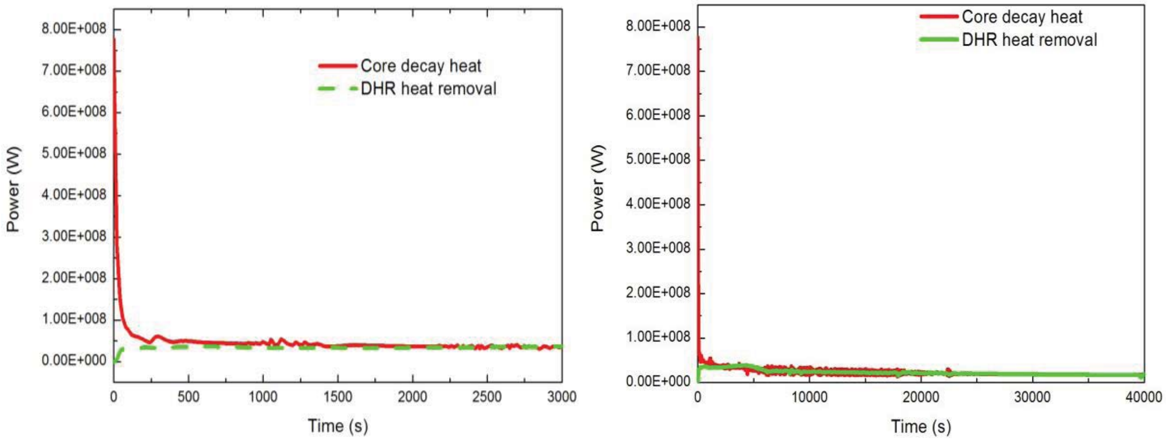


Figure 12. I2S reactor core decay heat curve

In Fig.18 it is demonstrated that the heat removal from three DHRs can nearly match the core decay heat after about 30 minutes and remove all the decay heat after around 20000 s. The reactor vessel pressure and core temperature variations are shown in Fig. 19 and 20. The maximum RPV pressure remains below the design pressure. Also the core temperature is kept within acceptable levels.



(a) **(b)**

Figure 18. Variations of decay heat and DHRs heat removal vs time: (a) Short term; (b) Long term

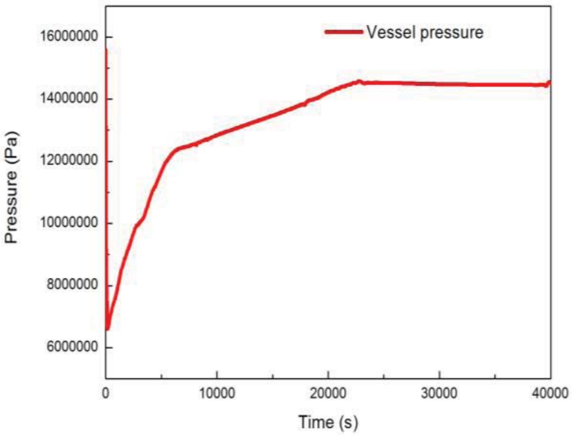


Figure 19. Variations of primary pressure vs time

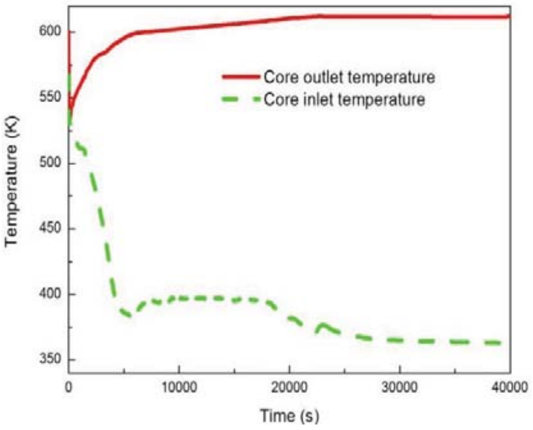


Figure 20. Variations of core inlet and outlet temperatures vs time

5. CONCLUSIONS

In this paper, a passive DHRS is proposed for the I^2S-LWR design. The DHRS system is optimized and its performance is investigated against a SBO accident using the best-estimate thermal-hydraulic code RELAP5.

It has been demonstrated that three out of four DHRS trains are sufficient to successfully remove the core residual heat in the event of a SBO transient. It has also been demonstrated that indefinite cooling, using atmosphere as the ultimate heat sink, can be achieved. This work is meaningful for the I^2S-LWR safety improvement.

ACKNOWLEDGMENTS

This research has been supported by the Chinese Scholarship Council and by the US DOE Office of Nuclear Energy's Nuclear Energy University Programs (NEUP).

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