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Reactor Cavity Cooling System with Passive Safety Features on RDE: Thermal Analysis During Accident

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ABSTRACT

Reaktor Daya Eksperimental (RDE) is an experimental power reactor based on HTGR technology that implements inherent safety system. Its safety systems are in compliance with "defense in depth" philosophy. RDE is also equipped with reactor cavity cooling system (RCCS) used to remove the heat transferred from the reactor vessel to the containment structure. The RCCS is designed to fulfil this role by maintain the reactor vessel under the maximum allowable temperature during normal operation and protecting the containment structure in the event of failure of all passive cooling systems. The performance and reliability of the RCCS, therefore, are considered as critical factors in determining maximum design power level related to heat removal. RCCS for RDE will use a novel shape to efficiently remove the heat released from the RPV through thermal radiation and natural convection. This paper discusses the calculation of RCCS thermal analysis during accident. The RPV temperature must be maintained below 65ºC. The accident is assumed that there is no electricity from diesel generator supplied to the blower. The methodology used is based on the calculation of mathematical model of the RCCS in the passive mode. The heat is released through cavity by natural convection, in which the RCCS is capable to withdraw the heat at the rate of 50.54 kW per hour.

INTRODUCTION

Reaktor Daya Eksperimental (RDE) is a 10 MWth nuclear power reactor design based on HTGR technology [1, 2]. RDE implements passive safety systems. Its safety system is in compliance with "defense in depth" philosophy, which includes several stages of implementation i.e. to prevent failure and abnormal operation, control of abnormal operation and detection of failures, control of accidents within the design limitations, control of severe accident conditions of installation, including the prevention of the expansion of the incident and mitigating the consequences, and the mitigation of radiological consequences of significant release of radioactive material [3, 4]. Defense in depth philosophy of RDE has been applied starting from the multiple barriers in spherical fuel. The 0.5 mm radius UO_2 (uranium dioxide) kernels are coated with TRISO layers. The coatings mitigate and minimize the risk of the fission products release into the environment during accidents [5].

As mentioned earlier, the reactor safety systems is implementing defense in depth philosophy, supported by passive safety systems [8]. The latter implies that, even without human intervention, the safety system will perform correctly anyway. The multiple barriers act as a double barrier. In an emergency situation, the reactor will trip due the coolant temperature exceeding the limit or

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excessive reactivity occurs. In short, passive safety system is basically using the physics of gravity, mass density difference, air pressure difference, and others physics laws instead of engineered system. During passive safety system works, it is assumed that there is no electricity supply from diesel generator as backup power. Passive safety system is a safety system which does not require any action from the operator, as well as safety systems work automatically perform rescue action, although accidents as severe as any [9].

A Reactor Cavity Cooling System (RCCS) is equipped in RDE, functions as heat removal system. Heat transferred from the reactor vessel is removed to the environment so that the reactor wall does not overheat. The RCCS is installed in the cavity between the reactor vessel and the concrete structure. It is designed to maintain the reactor vessel under the maximum allowable temperature during normal operation and protecting the reactor concrete in the event of passive cooling systems [5]. RCCS performance and reliability are thus considered as critical factors in determining the maximum level of design power associated with heat removal. This paper evaluates and discusses RCCS capabilities in the event of a failure or unavailability of the cooling system. The maximum heat taken from the reactor vessel by the RCCS is estimated by using the calculation of RCCS heat transfer capability in passive mode.

THEORY

The RDE Inherent Safety

RDE is an inherently safe nuclear reactor, meaning that the reactor does not need any active safety intervention in the event of a depressurized loss of forced coolant (DLOFC) and pressurized loss of force coolant (PLOFC) [8, 9]. The reactor system automatically reverts back to a normal state after the shut-down transient. The goals of safety design in RDE are as follows.

HTGR is the base of RDE reactor. This reactor will experience an automatic shutdown if an accident were to happen. The spherical fuel with multi-layer system will reduce environmental release of fission products. This can be virtually guaranteed as long as the maximum fuel temperature remains below 1600°C. The main safety system feature of RDE is inherent safety. It relies on negative temperature coefficient of reactivity, in which during the reactor temperature increases, the power decreases so that the temperature does not exceed 1600°C. The fuel kernel is coated by 4 TRISO layers, namely porous carbon buffer (95 μm of diameter), inner pyrolytic carbon (40 μm of diameter), silicon carbide barrier (35 μm of diameter) and outer pyrolytic carbon (40 μm of diameter). The porous carbon coating accommodates gaseous fission product from the kernel [5]. Meanwhile, the other layers function to prevent the release of fission products. Such construction is considerably effective to contain the fission product from leaking into the coolant. Graphite pebble has melting point of about 2500°C, so that in case of fuel failure in which the temperature increase above 1500°C, it will not affect or damage the fuel integrity. In conclusion, there shall be no need for moving components to ensure that the safety targets are achieved.

The second goal is achieved by using a passive cooling system, one of them being RCCS. RDE has itself equipped with RCCS to remove the heat transferred from the reactor vessel to environment so that the reactor wall does not overheat. RCCS is a radiation shield made of steel pipes placed between RPV and concrete walls that serve to absorb heat radiation. The concrete surrounding the reactor functions as insulation. It is designed to remove the heat radiated by RPV through natural circulation so that the concrete does not receive excessive heat. The objective of most RCCS designs is to serve as an ultimate heat sink, ensuring the thermal integrity of the fuel, core, vessel, and critical equipment within the reactor cavity. During normal operation, the temperature achieved in the fuel surface is around 1000°C. In the accident of DLOFC, the fuel temperature rise up to approximately 1500°C [11], and will decrease again as the RCCS removes the heat. The reactor cavity passively transfers the heat from the RPV to the surrounding environment through radiation and conduction.

The PLOFC Accident in HTGR

Pressurized Loss of Force Coolant (PLOFC) is an event where the primary system helium flow stops while primary system remains pressurized [10]. The primary helium flow is automatically stopped upon reactor shutdown followed by post-shutdown cooling system operating to remove the decay heat. Two safety-related aspects of PLOFC are core heat up transient with the potential for delayed radioactivity release from the fuel, and the heat up of metallic structures and equipment, particularly in the upper plenum (e.g., control rod drives) and other components within primary system pressure boundaries and critical components. Since the primary system is still under pressure, natural circulation of helium within the core helps equalize the core temperatures with the maximum core temperature shifting into the top of the core. Helium recirculation consist of upflow in the center (hotter) region the fuelled areas and downflow in the cooler core area. However, it is more pronounced in the cooler reflector. The maximum fuel temperatures in the PLOFC events are typically well below prescribed accident limits [13].

D-LOFC Accident in HTGR

In certain cases, "leak-before-break" assumptions are allowed by regulatory authorities for limiting the magnitudes of large-pipe or vessel rupture scenarios that need to be considered. The major consequence of a D-LOFC is the long-term core heat up and potential radioactivity release into the confinement, and eventually, to the environment (filtered and/or unfiltered) [14]. Unlike the P-LOFC, heat transfer due to natural helium circulation within the core is negligible. In general, the reactor is designed so that the maximum fuel temperature in a D-LOFC should not exceed the point where any significant fuel failure is expected. Typically, the reactor design (rated) power level is selected based on this calculation of best-estimate maximum fuel temperature in a D-LOFC accident. The heat up of metallic structures and potential material damage within and outside the primary system also needs to be evaluated. During a depressurization, some of the primary circulating activity, including radioactive graphite dust, may be released along with the helium. Depending on the confinement design and break size, a large prompt helium release may go unfiltered. During the core heat up process, certain amount of fuel failures may occur although, by design, any heat up phenomenon should result in only minor releases. Piping breaks and depressurization that follows would cause pressure distribution transients within the reactor, which may be very dynamic for large breaks. Pressure redistributions and vibrations are need to be evaluated to ensure the structural stability of the reactor internals as would possible external damage in the reactor confinement building and to the RCCS in particular. The potential for RCCS failure may be greater in D-LOFC events. Failure modes need to be evaluated since long-term loss of the RCCS cooling function could lead to major RPV and cavity damage, and thus lead to a dependence on other less predictable ultimate heat sinks [15].

Reactor Cavity Cooling System of RDE

The special feature of modular HTR designs is a possibility of removing the decay heat from the reactor pressure vessel (RPV) surface without exceeding the permissible fuel temperature and RPV temperature. In addition, there is a heat sink via the supports and attachments of the reactor and steam generator vessel unit and via the fuel discharge nozzle. The heat is transferred from the RPV to the RCCS surface cooler that is placed in the empty space of the reactor cavity. The RCCS performs the following functions:

- During normal operation and in the course of the cooldown by the main heat removal loop via the SG and steam-water circuit, the RCCS removes heat from the RPV surface, supports of the vessel unit and from the fuel discharge nozzle, and limits the temperature of the reactor cavity concrete.
- If it is impossible to accomplish the cooldown via the main heat removal loop, the RCCS removes the reactor decay heat and maintains the temperature of the fuel, RPV, reactor cavity concrete within the permissible limits.

The RCCS consists of three independent heat removal trains [12]. One operating train alone is sufficient to cool down the reactor. Two other RCCS trains incorporate surface cooler, headers that connect surface cooler tubes into sections, torus headers that join sections of one train, connecting pipelines, evaporator heat exchanger that consists of a water tank and a heat exchanger, and primary measurement transducers.

The coolant moves in two RCCS trains by natural circulation. Its coolant is distilled water. The configuration of the third RCCS train is analogous to the two above ones except it lacks of evaporator heat exchanger. The headers of this RCCS train are connected to the reactor plant equipment cooling system. The coolant flows within it by forced circulation that is ensured by pumps of the reactor plant equipment cooling system. Likewise, the coolant of the reactor plant equipment cooling system is also distilled water.

The RCCS schematic diagram is shown in Figure 1. The surface cooler of each of the two RCCS trains consists of separate sections. Each section is made of vertical U-tubes. The tubes of each section are joined together at their upper portions by two section headers (one supplies, and the other one removes the cooling water circulating inside the tubes). On the water side, the U-tubes are alternately connected to respective sections of different RCCS trains. Every third tube in the tube bundle is connected to one inlet header and one outlet header, respectively. Thus, with one or two RCCS trains failed, the heat removal will be guaranteed for the entire perimeter of the surface cooler.

The height of the surface cooler sections is equal to the height of the reactor cavity. Each tube in the section has a bend in its lower portion to compensate for temperature-induced displacements. The tube segments that receive the water cooled in the evaporator heat exchanger are placed closer to the reactor cavity wall surface. The surface cooler tubes are attached to a shield made of sheet steel. This shield between the surface cooler and the reactor cavity concrete reduces the reactor cavity concrete heat up produced by thermal radiation from the RPV. The gap between the surface cooler and the concrete is sealed such that air streams do not enter the gap. The surface cooler sections are evenly distributed around the RPV and attached to the vertical wall of the reactor cavity. The fastening elements of the sections allow temperature-induced downward displacements of the sections. The RCCS conceptual design of RDE is shown in Figure 1. Detail parameters of the reactor cavity and water cooled panel, like shown in Table 1.

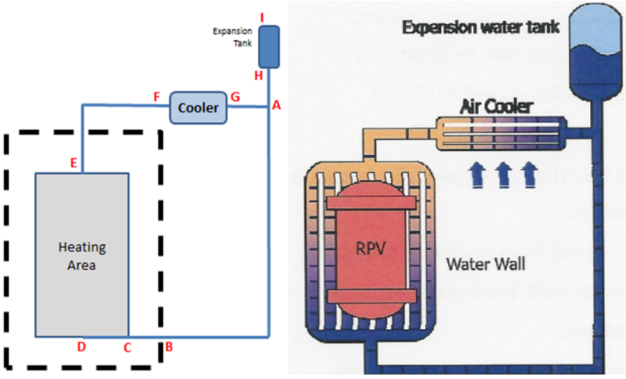

Fig 1. The RCCS conceptual design of RDE

Table 1. Detail parameters of the reactor cavity and water cooled panel

Parameter	Dimension (m)
Height of reactor cavity	12.8
Diameter of reactor cavity	6
Diameter of reactor pressure vessel	4.36
Diameter of water cooled panel	5.9
Height of water cooled panel	9.5
Thickness of steel sheet	0.005
Outer diameter of water cooled pipe	0.032
Inner diameter of water cooled pipe	0.026
Pitch of water cooled pipe	0.13

METHODOLOGY

This paper discusses the calculation of RCCS thermal analysis during the station blackout (SBO) accident. All of active cooling systems were assumed to be failed when SBO occurred and the heat removal is conducted by RCCS. The SBO is assumed that there is no electricity from diesel generator supplied to the blower. The methodology used is based on the calculation of heat transfer capability of the RCCS in the passive mode. The active one is the piping system of circulated water around RPV to discharge the heat through cooling tower. The passive mode works during the failure of active mode, and the heat is release through cavity by natural convection.

Experimental facility description

As shown in Figure 1, the number of RCCS loop is two loops, with 50 heating pipe on each loop as standpipes. All components were enclosed with high temperature materials. The concrete behind the vessel was made of an insulating material to limit heat losses. The operational thermal parameter of RCCS, like shown in Table 2.

Table 2. The operational thermal parameter of RCCS

Parameter	Data
Number of RCCS Loop	2 loop
Number of heating pipe per loop	50 pipes
Height of Heating Area, H1 (D-E)	9.5 m
Diameter of cooled pipe	2 inch
Flowrate in cooled pipe	0.16575 kg/sec
Reactor Cavity Radius (D-B)	3 m
Reactor Cavity Height	12.5 m
Reactor Cavity Concrete Thickness	1 m
Center Reactor to Cooled Pipe Center (D-A)	4.1 m
Height E-A	2 m
Height D-A	12.5 m
Pipe lenght upstream heating area	16.6 m
Pipe lenght downstream heating area	6.1 m
Flow rate of heating pipe inlet	0.03315 kg/sec
Water temp. upsteam of heating area	312 K
Water density in upstream of heating area	990.07 kg/m^3
Water temp. Downsteam of heating area	319.599 K
Water density in Downstream of heating area	985.0863 kg/m^3

RESULTS AND DISCUSSION

The RCCS is designed as the ultimate heat sink. It ensures that the thermal integrity of the nuclear fuel, the core, the Reactor Pressure Vessel (RPV), and all equipment in the reactor cavity is achieved. At normal operation, the RCCS ensure that the concrete structure surrounding the RPV is kept below 65°C and below 125ºC in case of total loss of the primary helium coolant accident. The more detailed conceptual design of RCCS is shown in Figure 1.

The heat from the RPV then discharged to the environment through the cooling tower. The passive system flows by natural convection as a result of the difference between hot and cold water temperature. Passive cooling systems have many advantages over normal cooling systems. By using a passive system, the design, installation, operation, and maintenance of the cooling system is simplified compared to a normal cooling water pumping system. The number of components of a passive cooling system is considerably less than that of a normal cooling system. The total of 80% reduction in pipe usage is possible if a passive cooling system is used [7,8]. This makes a passive cooling system both very economically as well as functionally competitive. The fact that a passive cooling system uses no mechanical components makes the system very reliable. The reactor can thus be regarded as inherently safe, because if the system has a very high reliability, the chance of a breakdown is very small. Thus, there is a very small possibility that the reactor failed to be maintained well within the specified allowed temperatures.

The RCCS is designed with stand pipes and installed surrounding the RPV. The water is used as cooling system. The RCCS has passive operations mode as stated. The water from the storage tank circulated to the stand pipes and removed the heat from the vessel. Water pumped back to the storage tanks and the heat released to the environment via cooling tower. If SBO occurred, the RPV cooling is conducted by the cavity between RPV and concrete. The air removed the heat from RPV by natural convection and still capable to maintain temperature below its design limit. The cavity connected to the atmosphere directly and the heat can be released. The fuel temperature will decrease until 800°C within 20 days.

We will calculate heat loss during the station blackout condition, using the following equations:
Head Loss due to friction along pipe:

$$\mathrm{hf} = \mathrm{f}\frac{\mathrm{L}}{\mathrm{D}}\frac{\mathrm{V}^2}{2\mathrm{g}} \tag{1}$$

Pressure Drop:

$$\Delta p = f\ \frac{L}{D}\frac{\rho V^2}{2} \tag{2}$$

$$K = \frac{K_1}{Re} + K\infty\ (1 + \frac{K_d}{D_n^{0.3}}) \tag{3}$$

Heat Loss :

$$\mathrm{h_L} = \mathrm{K}\frac{\mathrm{V}^2}{2\mathrm{g}} \tag{4}$$

where:

hf = Minor losses
f = Darcy friction factor
L = Length of pipe
v = flowrate velocity
D = diameter of pipe
g = gravitational acceleration
ρ = density
K = resistance coefficient
Re = Reynolds number
Dn = Dynamic viscocity
Kd = coefficient of friction
hL = Heat Loss

From the mathematical calculation, the following are the results of the heat loss, it's show in Table 3. But the comparation of heat loss transfer for normal and accident condition, like on Table 4.

Table 3. The convection heat transfer from RPV

Parameter	**Value**	**Unit**
Gas absolute viscosity	2.45E-05	kg/m/s
Air density	1.293	kg/m3
Gas kinematic viscosity	2.99E-05	m2/s
Air thermal expansion coeff	2.32E-03	1/K
Air thermal conductifity	0.00358	W/mK
Gr (grashof number)	4.74E+09	
Q-conv RPV	50542.758	W
Total Heat Loss Transfer from RPV	5.054E+04	W

Table 4. the Mathematical calculation of heat loss ttransfer on normal and accident condition.

Parameter	**Normal**	**Accident**	**Unit**
T-RPV [K]	507	673	K
T-RCCS [K]	353	373	K
Q from RPV [kW]	22.70588	50.54276	kW
T-inlet heating pipe [K]	312	312	K
T-outlet heating pipe [K]	313.1194	314.4917	K
Pressure Gain [kg.m^{-}1.s^{-2})] (no cooler, = max. Cooler pressure drop to allow natural circulation in the RCCS loop)	1138.179	2535.45	kg.m^{-}1.s^{-2})

During station blackout, the total heat transfer from RPV is 50.54 kW. This phenomenon can be illustrated graphically as shown in Figure 2.

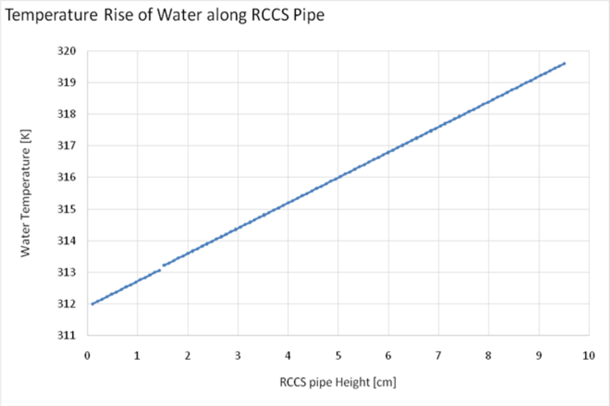

Fig 2. Diagram of temperature rise of water along RCCS pipe

From the figure, it can be explained that the temperature is proportional to the pipe height. The more pipe height, the higher the temperature. Effect of water density on pipe length is shown in Figure 3.

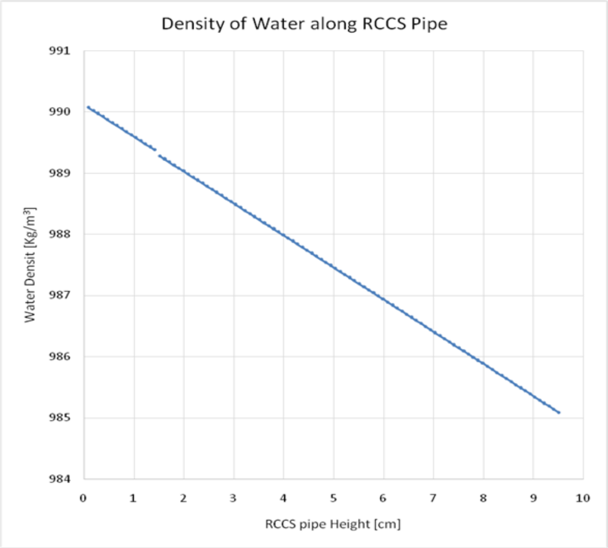

Fig 3. Density of water along RCCS pipe

From the figure, it is shown that the pipe height is inversely proportional to the water density. Meanwhile, the effect of mass flow of water along RCCS pipe is shown in Figure 4.

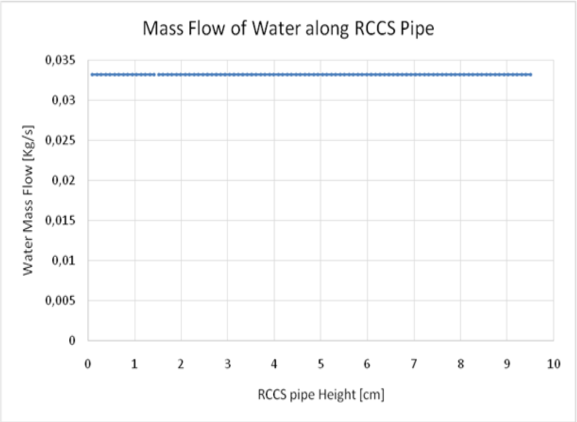

Fig 4. Diagram mass flow of water along RCCS pipe

It is understood that despite the pipe height increase, mass flow of water tends to remain constant. Referring to the Fukushima Daiichi accident, where tsunami caused station blackout, it is assumed here that all of electrical supply from outside plant is unavailable, the primary coolant blower fails, and the RCCS active mode also fails. Decay heat is removed by passive cavity cooling. RCCS eliminates the remaining decay heat through natural circulation. The heat is transferred by conduction to the pressure vessel and then radiation from the pressure vessel to RCCS via natural circulation. This mechanism is adequate to keep the core temperatures below the maximum design limit. The fuel maximum temperature allowable is 1600°C, while the highest normal operating fuel temperature should not be greater than 1250ºC. Fuel failure rates are extremely low below these temperatures and increases rapidly at much higher temperatures [16].

The heat from RPV is transferred to the environment by natural circulation. The SBO did no harm to the RDE because the RCCS are successful in maintaining the integrity of the fuel temperature beyond its design limit. The RCCS absorbs the heat from the reactor vessel directly by radiation and indirectly from the guard containment to atmosphere by natural convection.

CONCLUSION

RDE has an RCCS that serves to remove the heat transferred by the reactor vessel to the environment so that the containment structure does not receive excessive heat. The RCCS is designed to keep the reactor vessel below the maximum allowable temperature during normal operation and protect the reactor isolation structure. During SBO, all cooling systems are failed and heat removal is performed by RCCS. At such condition, the total heat transfer from RPV is 50.54 kW.

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