The RCCS Thermal Analysis during the Station Blackout Accident of RDE

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Abstract. RDE is designed based on HTGR technologies; it has an active, passive and inherent safety system. Defence in depth philosophy is conducted. The heat transferred from the reactor vessel to the structure of the containment is equipment in the RDE has a name is a reactor cavity cooling system (RCCS). During normal operation and protecting the reactor containment structure in the event of failure of all active cooling systems, the RCCS designed to take fulfill this role by preserving the vessel reactor under the maximum allowable temperature. Concerning heat dissipation design, RCCS assessment and resolution are considered as major factors in determining the maximum power level of heat dissipation. Active and passive mode is the equipment on RDE RCCS. This paper discusses the calculation of RCCS thermal analysis during the station blackout (SBO) accident. SBO occurred and the heat removal is conducted by RCCS when all of the active cooling systems were failed. Conditions will be safe if the RPV temperature must be maintained below 65ºC. There is no electricity from diesel generator supplied to the primer compressor, it will the SBO accident. The methodology used is based on the calculation mathematical model of the pebble bed modular reactor heat transfer capability of the RCCS in the passive mode. The passive mode works during the failure of active mode, and the heat is released through the cavity by natural convection. The RCCS is capable to withdraw the heat at 50.54 kW per hour and keep the reactor pressure vessel temperature below 65ºC at normal operation and below 125ºC during the station blackout.

Keywords: thermal analysis, RCCS, station blackout, RDE

1. Introduction

RDE (Reaktor Daya Eksperimental) has 10 MW thermal output is a nuclear power reactor conceptual design based on HTGR technology [1], [2]. RDE applies inherent safety systems including active and passive. The reactor safety system is generally carried out in the philosophy of "defence in depth" [3], that has a few stages of application, namely preventing failures and abnormal operations, controlling abnormal operations and failure detection, controlling accidents within design limits, controlling severe accident conditions, including preventing the expansion of incidents and reducing the consequences, and controlling of the radiological consequences of the huge release of radioactive material [4]. In-depth defence philosophy about RDE has been applied to start from various obstacles in ball fuel. The UO2 kernel (uranium dioxide) has graphite 0.5 mm in diameter [5]. The coated layer reduces and minimizes the risk of releasing fission products to the environment when accidents occurred [6].

The RDE safety systems are using defence in depth as mention in the first paragraph, and the implementation is supported by active, passive and inherent safety systems [7]. Passive safety system tools
passive nuclear safety is a design approach for safety features, implemented in nuclear reactors, which does not require active intervention from the operator or electrical/electronic feedback to bring the reactor to a safe shutdown state if it is of a particular type of emergency; the reactor safety system is done correctly [8]. The physical multiple barriers as a double barrier in an emergency reactor safety system, the reactor will trip because the coolant temperature over the limit or excessive reactivity occurs[9]. The inherent safety system is using the influence of differences in cooling, air pressure differences, gravity, mass density, and others [10]. During inherent safety system works, that there is no electricity backup power from diesel generator as an assumption into taken account. Inherent 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 [11].

In RDE, the heat releases from the RPV to the concrete surrounding is removed by RCCS. The RCCS is installed among the Reactor Pressure Vessel (RPV) and the concrete. It was built to accomplish this function by keeping the RPV below the maximum limit temperature on the normal operation. RCCS also protects the reactor concrete during in the accident of damage of all dynamic/active cooling systems [5]. The RCCS heat absorber structure shields the cavity wall around the reactor's active vessel. The reliability and performance of RCCS are important factors in justified the maximum design power level associated with heat removal. This research evaluates and discusses the ability of the RCCS in the event of a failure or unavailability of all other shutdown cooling systems. The heat maximum taken from the reactor vessel by RCCS is justified using the calculation of heat transfer capability of the RCCS in the passive mode.

2. Theory
2.1 The RDE Inherent Safety
RDE is a nuclear reactor with inherent safety, which means that the reactor does not require active safety intervention if there is a pressurized loss of force coolant (P-LOFC) and a depressurization loss on forced coolant (D-LOFC) [8] [9]. The RDE reactor system automatically returns to normal after the transient has ended. The safety design objectives at RDE are as follows:

- HTGR system as the base of an RDE reactor which is an internal system, this reactor will experience an automatic shutdown if there is an accident. The ball-shaped fuel with a layered system will reduce exposure to the fission products to the environment. The RDE fuel intends to use, 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 where the safety system relies on a negative coefficient of reactivity, during the reactor temperature increases; the reactor core temperature does not exceed 1600°C. The fuel kernel has 4 layers with porous carbon buffer (95μm of diameter) layer, inner pyrolytic carbon (40μm of diameter), silicon carbide barrier coating (35μm of diameter) and outer pyrolytic carbon (40μm of diameter). The characteristics of the porous carbon coating on the particle TRISO buffer can accommodate the fission product of the UO2 kernel [12]. Some layers will maintain the possibility of releasing fission products out of the TRISO. The fuel fabrication must perfect to prevent fission product leakage to the reactor cooling system. The graphite in the fuel kernel has a melting point temperature of 2500°C when the accident occurred and the temperature raised and reached 1500°C, the TRISO is not damaged. The safety target will be achieved without any need for moving the mechanical part. The TRISO particles will melt in the temperature above 2500 °C. The RCCS maintains the temperature by the passive cooling mechanism. The RCCS conceptual design of RDE is shown in Figure 1.
RCCS is a radiation shield made of steel pipes located between RPV and concrete walls that function to absorb the heat. The concrete surrounding the reactor will serve as insulation. This RCCS is designed so that it functions to reduce the heat generated by RPV through natural circulation so that the concrete does not receive excess heat. RCCS serve as a releasing heat sink and ensure that the core, fuel, and other critical component are maintaining its integrity. On normal operation, the temperature raised and reached the fuel surface is around 1000 °C. In case of DLOFC accidents, the fuel temperature rises to around 1500 °C \[9\] and will decrease again due to the reactor cavity cooling system. The reactor cavity passively transfers heat from the RPV to the surrounding environment through radiation and conduction cooling.

2.2 The DLOFC and PLOFC Accident in HTGR
Pressurized Loss of Force Coolant or PLOFC is events where the main system helium flow stops and the primary coolant system remains pressurized \[10\]. When the reactor is shut down followed by SCS (shutdown cooling system) operation to remove heat afterward, primary helium flow is automatically stopped. Two aspects related to PLOFC safety are the temporary heat core with the possibility for the release of residual radioactivity from the pebble fuel, and the heat of equipment and metal structures, especially in the upper plenum (for example, control rod drives) and others. The primary system pressure limits and important components. Due to the primary coolant system is still under pressure, the helium flow drives by natural circulation in the reactor helps equalize the core temperature with the maximum core temperature that migrates closer to the top of the core. Helium recirculation consists of the upper flow in the fuel area, in the lower flow in the side area and the central (hotter) area of the cooling core but more clearly in the cooling reflector. The maximum fuel temperature in a PLOFC event is usually far below the specified accident limit \[11\].

Depressurized Loss of Force Coolant or D-LOFC is an assumed long-term loss of primary system circulation and helium inventory. In the accident leak before the break, the limiting scale of pipe or vessel rupture assumptions are determined by the regulatory authority. The consequences of DLOFC are the probability of long term core heat up and radioactivity release to the reactor confinement and followed its
leakage to the environment. Even, there are some filters are conducted to mitigate the radioactivity release [12]. For the PLOFC, heat transfer in the reactor core caused by natural circulation can be ignored. In the DLOFC case, the maximum fuel temperature should be maintained below the limit of fuel failure is set. Usually, the power level is selected base on best estimate calculation of maximum temperature in the DLOFC accident.

The potential damage in metallic structure and material caused by temperature heat up within inside or outside of the primary system must be evaluated. In the depressurization, the graphite dust may be released cause by primary coolant flow. The quantity of helium release depends on the confinement design and break size. Some fuel damage may occur during the core heat-up process. The depressurization caused by piping breaks will cause transient pressure distribution in the reactor. It very fluctuates when the large breaks occurred. To ensure the structural stability, pressure redistributions and vibrations would need to be evaluated that impact to reactor internals and also RCCS. The possibility of RCCS failure is bigger in DLOFC comparing to the PLOFC. The damage scale of RCCS needs to be evaluated to consider the availability of long term heat sinks function and cooling [13].

### 2.3 Reactor Cavity Cooling System of RDE

The special feature of modular HTR designs is the possibility of removing the decay heat from the reactor pressure vessel (RPV) surface without exceeding the permissible fuel temperature and RPV temperature. Besides, 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 free 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 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 [13]. One operating train alone is sufficient to cool down the reactor. Two RCCS trains incorporate surface cooler, headers that connect surface cooler tubes into sections, torus headers that join sections of one train, connecting pipelines, an evaporator heat exchanger that consists of a water tank and a heat exchanger, primary measurement transducers.

The coolant moves in two RCCS trains by natural circulation. The RCCS coolant is distilled water. The configuration of the third RCCS train is analogous to the two above ones except for it has no evaporator heat exchanger. The headers of this RCCS train are connected to the reactor plant equipment cooling system. The coolant moves in this RCCS train by forced circulation that is ensured by pumps of the reactor plant equipment cooling system. The coolant of the reactor plant equipment cooling system is distilled water. The RCCS schematic diagram is shown in Figure 1. The surface cooler of each of the three 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 waterside, 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 nearer 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.
Table 1. Technical specification of RCCS

| Parameter                 | Units (m) |
|---------------------------|-----------|
| RPV diameter              | 4.36      |
| Reactor Cavity            |           |
| Height (HRC)              | 12.8      |
| Diameter (DRC)            | 6         |
| Water-cooled panel        |           |
| Diameter (DWC)            | 5.9       |
| Height (HWC)              | 9.5       |
| Steel sheet thickness (TWC)| 0.005     |
| Outer diameter (ODWC)     | 0.032     |
| Inner diameter (IDWC)     | 0.026     |
| Pipe pitch (PPWC)         | 0.13      |

3. Methodology

This paper discusses the calculation of RCCS thermal analysis when the station blackout (SBO) accident occurred. It is assumed, that all of the active cooling systems were failed during SBO and the heat release is taken by RCCS. The RPV temperature must be maintained below 65°C. The SBO is assumed that diesel generator is not available to supply electricity to the compressor. The calculation of the heat transfer capability of the RCCS in passive mode is done and use as a methodology. The active one is the piping system circulated water around RPV and discharge the heat through the cooling tower. The passive mode works during the failure of active mode, and the heat is released through the cavity by natural convection.

4. The RCCS Testing Facility Description

The RCCS experimental facility of RDE is shown in Figure 1. The RCCS loop is two loops, and there is 50 heating pipe per loop as a standpipe. All the components were made and cover with high-temperature strength materials. The concrete surrounding the vessel was built of an insulating material to reduce and decreasing heat losses to the environment. From Figure 1, the height of the heating area (D-E) is 9.5 m. RCCS radius (B-D) is 3 meters. RCCS height is 12.5 meters. Concrete thickness is 1 meter, pipe length upstream of heating area is 16.6 meters, pipe length of downstream heating area is 6.1 meters. The stand heating pipe has specifications like the flow rate of heating pipe inlet is 33.15 gr/sec. Water temperature at heating pipe inlet 39 oC. Water temp. Upstream of heating area 312 K, Water density in upstream of heating area 990.069 kg/m³. The velocity of water upstream of the heating area is 0.00089 Ns/m². Water temperature at downstream of heating area is 319.599 K. Diameter of the cooling pipe is 2 inches, flowrate in the cooling pipe is 165.75 gr/sec, crosssection of cooling pipe is 2.0264 e⁻³ m².

5. Results and Discussions

HTGR has 2 heat removal systems, the first system is an energy conversion system and the second is the shutdown cooling system as seen in Figure 2a. Under normal operation, both systems are used to remove the heat core and decay heat from the fuel in the core. These systems called active cooling systems. If the two active systems fail, the RCCS serve as cooling for the RPV. This system is shown in Figures 2b and 2c.
Figure 2. The two shutdown cooling systems (SCS) in RDE: a) active SCS, b) passive RCCS

The RCCS of RDE is built to transfer the heat to the concrete and environment. The RCCS maintains the thermal integrity of the core, the Reactor Pressure Vessel (RPV), the nuclear fuel, and all equipment in the reactor cavity is achieved. The two conditions that should maintain by RCCS are that in normal operation, the concrete structure surrounding RPV is kept below 65 °C, and in the case of total loss primary coolant accident below 125 ºC. The conceptual design of RCCS in more detail is shown in Fig. 3.

Comparison to the normal cooling system, passive cooling systems have many advantages. The design, installation, operation, and maintenance of the passive cooling system are simpler than the normal cooling water pumping system. The passive cooling system components are less than a normal cooling system. The total reduction is about 80 % of pipe usage if a passive cooling system is used [7, 8]. A passive cooling system is very economically and functionally competitive; the system has without mechanical components and
affected to the very reliable system. The RDE has an inherent safe system, the reactor system has very high reliability, and the chance of a breakdown is small. The reactor will not be kept within specified allowed temperature and has a good reliable system.

The RCCS installed surrounding the RPV and is designed with standpipes. The water is used as the cooling system. The RCCS has two mode operations i.e. active and passive mode as stated. The water from the storage tank circulated to the standpipes and took the heat from the vessel. Water pumped back to the storage tanks and the heat release to the environment via a cooling tower. If SBO occurred, and the water pumps were not available, the RPV cooling is conducted by the cavity between RPV and concrete. The air took the heat from RPV by natural convection and still capable to maintain the 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. The K constant is calculated by equation (1), heat loss by equation (2) heat loss due to friction along the pipe by equation (3), and pressure drop is calculated by equation (4), respectively.

\[ K = \frac{K_1}{Re} + K_\infty \left(1 + \frac{K_d}{D^{0.3}}\right) \] ..........................(1)

\[ h_L = \frac{K V^2}{2g} \] .................................(2)

\[ h_f = f \frac{L V^2}{D 2g} \] .................................(3)

\[ \Delta p = f \frac{L \rho V^2}{2} \] .................................(4)

### Table 2.

From the mathematical calculation, the following results are obtained

| Parameter                          | Normal   | Accident | Unit  |
|------------------------------------|----------|----------|-------|
| Temperature-RPV                   | 507      | 673      | °K    |
| Temperature-RCCS                  | 353      | 373      | °K    |
| Q (heat) from RPV                 | 22.70588 | 50.54276 | kW    |
| Temperature-inlet heating pipe    | 312      | 312      | °K    |
| Temperature-outlet heating pipe [K]| 313.1194 | 314.4917 | °K    |
| Pressure Gain [Kg/(m.S^2)] (no cooler, = max. Cooler pressure drop to allow natural circulation in the RCCS loop) | 1138.179 | 2535.45  | Kg/(m.S^2) |

During SBO, the total heat transfer from RPV to the RCCS is 50.54 kW. This phenomenon can be illustrated graphically as shown in Figure 4. The temperature is proportional to the height pipe. The higher pipe RCCS increasingly, as well as the temperature. Figure 5 shows the height pipe (heating pipe) is inversely proportional to the water density. Figure 6 shows the water mass flow vs pipe height in RCCS.
Figure 4. RCCS pipe height vs water temperature

Figure 5. The height pipe (heating pipe) is inversely proportional to the density of water.
Refer to the Fukushima accident that the tsunami-affected to station blackout (SBO). During the SBO, it is assumed that all of the electrical supply from the outside plant is not work, the primary coolant compressor fails to operate, and the RCCS active mode also fails. Because the RCCS water pump also assumed to fail, heat is transferred by conduction from the reactor cavity to the earth and surrounding areas. Decay heat (residual heat) is removed by the passive cavity cooling system.

RCCS removes the remaining decay/residual heat in the reactor core by natural circulation. The heat is shifted by conduction to the pressure vessel and then radiation from the pressure vessel to RCCS via natural circulation. This mechanism is perfectly adequate to keep the core temperatures below the maximum design limit. In the normal operation, the fuel maximum temperature is 1000°C. If there is no helium coolant circulated in the primary system, the fuel temperature will increase to 1500°C. While fuel temperature increase from 1000 to 1500 °C, at the same time the RCCS removed the RPV heat and, continuously decreasing the fuel temperature until equilibrium temperature reached. The fuel maximum temperature allowable is 1600°C. The heat from RPV is transferred to the earth by natural circulation. The SBO did not harmful to the RDE, because the RCCS can maintain the integrity of the fuel temperature beyond its design limits. The RCCS absorbs the thermal energy from the reactor vessel directly by radiation and indirectly from the guard containment to the atmosphere by natural convection.

6. Conclusions
Reactor cavity cooling system (RCCS) of RDE is built to remove the heat from the reactor vessel to the structure of the containment. It is assumed, that all of the active cooling systems were failed during SBO and the heat release is taken by RCCS. The SBO is assumed that diesel generator is not available to supply electricity to the compressor. RCCS in RDE has two types of equipment, first is the active mode and the second is passive mode equipment. The active one is the piping system circulated water around RPV and discharge the heat to the cooling tower/atmosphere. The passive mode works during the failure of active mode, and the heat is released through cavity space. It is concluded that the RCCS of RDE is capable to maintain the RPV temperature < 65°C at normal operation and below 125°C during the Station Blackout (SBO) accident.

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References
[1] Sriyono, R. Kusmastuti, S. Bakhri, and G. R. Sunaryo, “Analysis of helium purification system
capability during water ingress accident in RDE,” in *Journal of Physics: Conference Series*, 2018.

[2] M. Subekti, S. Bakhri, and G. R. Sunaryo, “The Simulator Development for RDE Reactor,” *J. Phys. Conf. Ser.*, vol. 962, no. 1, 2018.

[3] R. Swart and R. T. Dobson, “Thermal-hydraulic simulation and evaluation of a natural circulation thermosyphon loop for a reactor cavity cooling system of a high-temperature reactor,” *Nucl. Eng. Technol.*, no. xxxx, 2019.

[4] T. S. and G. Sunaryo, Sriyono Sriyono, “Carbon dust in primary coolant of RDE : its problem and solution,” *Tri Dasà Mega*, vol. 22, no. 3, 2018.

[5] S. Sriyono, R. Kusumastuti, A. Hafid, and D. H. Salimy, “Temperature profile analysis on cryogenic activated carbon column of helium purification testing facility,” *AIP Conf. Proc. 2180*, 020046, vol. 020046, no. December, 2019.

[6] W. Peng, T. Zhang, X. Sun, and S. Yu, “Thermophoretic and turbulent deposition of graphite dust in HTGR steam generators,” *Nucl. Eng. Des.*, vol. 300, pp. 610–619, 2016.

[7] L. Capone, Y. A. Hassan, and R. Vaghetto, “Reactor cavity cooling system (Rccs) experimental characterization,” *Nucl. Eng. Des.*, vol. 241, no. 12, pp. 4775–4782, 2011.

[8] Sriyono, “The adsorber component addition in ChemCAD software palette for helium purification modeling and simulation.” Jurnal PRIMA, Jakarta, pp. 19–25, 2018.

[9] Siti Alimah Sriyono, “Kajian Sistem Pemurnian Helium Reaktor HTGR Berdaya Kecil,” *J. Pengemb. Energy Nukl.*, vol. 18, pp. 123–133, 2016.

[10] M. Bucknor, D. Grabaskas, A. J. Brunett, and A. Grelle, “Advanced Reactor Passive System Reliability Demonstration Analysis for an External Event,” *Nucl. Eng. Technol.*, vol. 49, no. 2, pp. 360–372, 2017.

[11] A. Frisani, *Analysis of the Reactor Cavity Cooling System for Very High Temperature Gas Cooled Reactors Using CFD Tools*, no. May. 2010.

[12] K. Natesan, A. Purohit, and S. W. Tam, “Materials Behavior in HTGR Environments,” *NUREG/CR-6824*, p. 85, 2003.

[13] H. C. Wei, “Reactor Cavity Cooling System Heat Removal Analysis for a HTGR,” *Master Thesis*, vol. 1, no. 1, pp. 1–76, 2009.