Preliminary Study of DLOFC Accident in HTGR using GRSAC

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Abstract High Temperature Gas-cooled Reactor (HTGR) is one of the Generation-IV reactors that has many advantages and very promising to be utilized in the future. National Nuclear Energy Agency of Indonesia (BATAN) has a program to build a non-commercial power reactor (RDE) that will be based on the pebble-bed type of HTGR. To support this program, the research and development activities in HTGR have been conducting recently. One of the important aspects to be studied is accident analysis to assess the behavior of HTGR during the accident and to anticipate the consequences that might be caused. The purpose of this work is to study the Depressurized Loss of Force Coolant (DLOFC) accident on HTGR by using Graphite Reactor Severe Accident Code (GRSAC). The type of HTGR used as a case study is PBMR-400. This work was begun with the preparation of GRSAC input for reactor parameter including reactor design, core layout design, primary cooling loop design, graphite properties and material properties, cavity design, vessel design, and fission product release. It was assumed that there is an initial event that causes the reactor depressurization and the coolant loss during the time range of 13 seconds. During this time, the reactor pressure dropped from 91.75 kg/cm² to 1.05 kg/cm² and the coolant flow reduced from 192.53 kg/s to 0.29 kg/s. Two types of DLOFC event were studied which are DLOFC with scram and DLOFC without scram. The behavior of the fuel temperature was then analyzed during the time range of 100 hours after the DLOFC accident. It was obtained that the maximum fuel temperature was reached at the time of 60 hours after the accident. The maximum temperature after the DLOFC with and without scram accident is 1545°C and 1740°C, respectively. The results of this work were also compared to the results of benchmark work on PBMR-400 conducted by American Nuclear Society and it showed a good comparison. At the end, this work will be very beneficial to be implemented in the RDE program.

1. Introduction
Badan Tenaga Nuklir Nasional (BATAN) plans to build a 10-MWth High Temperature Gas-cooled Reactor named Reaktor Daya Eksperimental (RDE). This plan is supported by research and development activities to enhance the progress of RDE construction. Many aspects are needed to be investigated regarding the safety analysis of RDE. One of those aspects is the thermal safety of RDE in terms of temperature profile of RDE fuels in normal condition as well as in accident condition. The analysis of thermal safety of RDE can be performed using thermohydraulic code, in this work the GRSAC (Graphite Reactor Severe Accident Code) code is used. GRSAC is a code developed by Oak Ridge National Laboratory (ORNL) USA used for analyzing postulated initiated events in gas cooled reactor. The default use of GSRAC is for Pebble Bed Modular Reactor (PBMR). The use of GRSAC code can be...
extended to another type of HTGR by performing the input parameter modification in accordance with the reactor type that will be analyzed.

This work is aimed to study the characteristic of GRSAC code in calculating accident condition of HTGR. The type of HTGR used in this study is PBMR-400. This work will be a preliminary study before conducting thermal safety analysis of RDE using GRSAC. The accident condition analyzed in this work is depressurization accident. Depressurization is the event of pressure loss in a high-pressure system over a period of time. If depressurization occurs in the primary / secondary system of the reactor, this event will have an impact on the safety of the reactor operation. In the Light Water Reactor (LWR) reactor, high pressure on the primary system serves to keep the cooling water from picking up the heat of the fission reaction and then boiling at a temperature much higher than the boiling temperature of water at atmospheric pressure. In the High Temperature Gas-cooled Reactor (HTGR) reactor type, high pressure on the primary system serves to keep the cooling gas (helium) in order to extract the high temperature heat of the fission reaction results. Therefore, high pressure on the reactor primary system is critical to be maintained and the incidence of depressurization is critical to anticipate for the safe operation of the reactor.

Depressurization events in the primary system may occur when there is a leak in one of the pipes in the primary system. Due to leakage of this pipe, the pressure on the primary system will decrease slowly or drastically depending on the size of the leakage pipe. The larger the leak diameter, the faster the pressure decreases. When pressure loss persists, the primary system will reach atmospheric pressure and there is equilibrium between the primary system and the reactor building.

The occurrence of pressure loss can be accompanied by the occurrence of coolant flow (helium) from the primary system to the reactor buildings. This coolant flow rate also depends on the pipe leakage size. The larger the pipe leak diameter, the more coolant that passes out of the primary system. The occurrence of pressure loss followed by a cooling loss is known as Depressurized Loss of Coolant Accident (DLOFC). When the equilibrium pressure of the primary system with the reactor building is achieved, another consequence that may arise is the entry of air from outside to the primary system that occurs through natural convection mechanisms. This event is known as air ingress. The DLOFC event - either followed by an incident of air ingress or not - belongs to the type of accident beyond the basic design (Beyond Design Basic Accident / BDBA) on HTGR [1].

This study aims to assess the incidence of depressurization accidents in HTGR reactor. The method used is through simulation using Graphite Reactor Severe Accident Code (GRSAC) program. GRSAC is a computer program for analyzing postulated initiated accident events in gas-cooled reactors [2]. The types of accidents that are simulated are accidental loss of pressure followed by coolant loss (DLOFC). The GRSAC program was originally created for accident analysis on the Pebble Bed Modular Reactor (PBMR) reactor developed by South Africa. However, in this research we will try to parameterize the GRSAC program for the analysis of pebble bed reactor accident with 10 MW power, which in this case HTR-10 reactor is used as the study object. Since the PBMR reactor configuration is very different from HTR-10, such as the presence and absence of a central reflector, the change of GRSAC parameters from PBMR to HTR-10 is a challenge.

The ultimate goal of accident analysis with GRSAC is so that it can later be applied to the Experimental Reactor (RDE) to be built in Indonesia [3]. As a first step, an accident simulation with GRSAC for the PBMR reactor will be done to understand how GRSAC works while collecting the HTR-10 parameters for input into the GRSAC input. After successful with the new HTR-10 then it will be applied to RDE. Accident scenarios simulated with GRSAC are DLOFC accidents. The output of this simulation is the fuel temperature profile during the accident as well as the maximum temperature that may be reached by the fuel after the accident.

2. Theory

The very rapid occurrence of depressurization has the consequence of inventory release in the primary system to the reactor building without filtering process such as graphite dust contaminated with fission products coming out of defective fuels such as Cs-137. In addition, the rapid depressurization process also has the consequence of damaging components outside the primary system due to the release of very hot helium with very high momentum.

The exhausted cooler causes the fuel temperature to increase. However, because the negative temperature coefficient on HTGR causes the reactor to shutdown immediately so that the heat in the fuel comes from the radionuclide decay inside the fuel. The mechanism for discharging core heat removal
remains a challenge to the design of the HTGR reactor whether heat will be disposed of by active, passive, or by natural convection [4].

In addition to the heat dissipation mechanism in the event of depressurization accident, the maximum temperature that will occur in the fuel is also an important thing to know. This is due to the possibility of damage to fuel if the temperature exceed the maximum limit of fuel material capabilities before the end of damage. The fuel of the HTGR reactor is generally in the form of micro uranium spheres coated by three isotropic layers (TRISO) i.e. inner pyrolitic carbon (IPyC), silicon carbide (SiC) and outer pyrolitic carbon (OPyC) [5]. The maximum temperature of the fuel allowed to keep the fuel in good condition is about 1600°C [6]. Some computer programs used to calculate the maximum fuel temperature in the event of depressurization are TINTE, PEBBED-THERMIX, and GRSAC.

Besides the temperature rise that will occur in fuels under conditions of depressurization accidents, fuel damage due to oxidation may also occur. In the event of depressurization, after an equilibrium pressure exists between the inner and outer parts of the reactor vessel, the air from the outside may enter the pressure vessel through the pipe leakage area. This event is known as air ingress [7]. This air input process can occur through the mechanism of molecular diffusion or the natural air mixture due to the difference in temperature and concentration of each air component in the reactor. One of these air components is the oxygen and oxygen that will oxidize the graphite in the fuel to produce carbon monoxide (CO) and carbon dioxide (CO2). The oxidation of graphite in this fuel causes the graphite layers in the fuel to be thinner thus reducing the likelihood of resulting in the release of fission products out of fuel [8].

The concentration along with the activity of the fission product out of fuel (sourceterm) in the event of a depressurization accident is also an important thing that needs to be studied. Before estimating the amount of fission products coming out, the amount of fission product inventory in the fuel at the time of the incident must be calculated first. One fission product inventory can be calculated using the ORIGEN2.1 computer program [9]. Once inventory data is obtained, the degree of fuel damage occurring in a depressurization accident due to very high temperatures or due to fuel damage due to oxidation is necessary to be analyzed. Some of the computer programs that can be used for analysis of HTGR fuel damage are PANAMA, FRESCO, GRSAC, PEBBED, and others.

The DLOFC accidents are accidental stress losses caused by pipe leaks on the reactor primary system. As a result of this pipe leakage, the pressure in the primary system will decrease drastically in a very short time. The DLOFC accidents can be assumed to consist of two types of occurrences i.e. DLOFC without scram and DLOFC with scram. DLOFC without scram accidents is when the primary system loses pressure, indirect reactor scram but occurs transient state for some time, fuel temperature rises, and reactor power down. In DLOFC without scram events it is possible that the reactor can reach critical back after an interval of several hours. In contrast, DLOFC with scram accidents is when there is a loss of pressure on the primary system, the reactor automatically scrams instantly within a few seconds. Both types of DLOFC accidents result in different fuel temperature profiles.

3. Methodology

In this preliminary study, a DLOFC accident analysis with GRSAC was conducted for PBMR type reactors. The purpose of this PBMR simulation is to understand the workings of GRSAC so that it can be known the meaning of each parameter on PBMR which will then be determined correlation with HTR-10 reactor. The initial step before performing the simulation is to enter the reactor parameters in the GRSAC input section. There are many parameters in the input section of the GRSAC program that must be completed in order for the simulation to run. The parameters are grouped into several categories: Nuclear Design, Core Layout Design, Primary Cooling Loop Design, Graphite Properties and Material Properties, Cavity Design Reactor, Vessel Design, and Fission Product Release. The PBMR parameter is available in the GRSAC program while the determination of the correlation as well as the parameter collection for HTR-10 is done by referring to the GRSAC manual book, related papers and references on accident analysis on PBMR and HTR-10.

After preparing the input, the next step is to simulate the initial condition to obtain steady state condition, which contains several parameters including reactor power, inlet and outlet temperature, primary pressure, primary flow rate. After steady state condition is reached, the accident simulation will be done. The accident scenario is a DLOFC accident, with scram and no scram. The duration of DLOFC events is assumed to occur within 13 seconds. The simulation results discussed are the fuel temperature profile at and after the accident.
4. Results And Discussion

4.1 DLOFC Accident Simulation Results for PBMR-400

Simulation of initial/normal condition

Before performing an accident simulation on the GRSAC program, a simulation must be performed to obtain initial condition until the steady state is reached. The simulation results for the steady state conditions of the core of the PBMR-400 reactor can be seen in Table 1.

Table 1. Steady state conditions of reactor core of PBMR-400

| Parameter           | Value | Unit     |
|---------------------|-------|----------|
| Power               | 400   | MW       |
| Inlet temperature   | 496   | °C       |
| Outlet temperature  | 892.58| °C       |
| Primary pressure    | 91.75 | kg/cm²   |
| Thermal Equilibrium | 99.28 | %        |
| Primary flow        | 192.53| kg/s     |

4.2 Simulation of accident condition

In the GRSAC program, accident scenarios are determined within the programmed input window in the event time. For DLOFC accident events, from several references of available benchmark projects, generally the incidence of depressurization and coolant loss in the primary system is assumed to occur within a very short span of 13 seconds [10]. However, several other studies also exist that assume the time range of the depressurization event and the coolant loss is assumed to occur within 0.5 seconds [11]. The fuel temperature calculation on the DLOFC accident benchmark project on PBMR-400 has been done by using computer programs such as DALTON - THERMIX, DORT - TD / THERMIX - DIRECTOR, TINTE, PARCS, DALTON - THERMIX, and others.

Simulation with GRSAC at this time is done for two types of incidents that are DLOFC accidents with scram and DLOFC accident without scram. Each accident scenario is defined in programmed input in GRSAC. The time range of the pressure loss used is 13 seconds. The simulation time used is for 10,000 minutes (~ 166 hours) with a 5 minute time step.

4.3 DLOFC Accident with scram

In a DLOFC accident with a scram, shortly after a drop in pressure on the primary system, the scram reactor is immediate. For 13 seconds at the beginning of the event, the primary pressure decreased from 91.75 bar to 1 bar (atmospheric pressure) and the helium flow in the primary system decreased from 192.53 kg / s to 0.29 kg / s. Some of the core parameters of PBMR-400 at 10,000 minutes after the accident event can be seen in Table 2.

Table 2. Condition after DLOFC accident with scram

| Parameter           | Value | Unit     |
|---------------------|-------|----------|
| Power               | 1.59  | MW       |
| Inlet temperature   | 505   | °C       |
| Outlet temperature  | 750   | °C       |
| Primary pressure    | 1.05  | kg/cm²   |
| Primary flow        | 0.29  | kg/s     |

The results for the maximum temperature and average temperature of the fuel for 100 hours after the DLOFC event are shown in Figure 1. From the figure it can be seen that the maximum temperature on fuel...
is reached after about 60 hours which is 1545°C. The average temperature of fuel after 40 hours with a value of 1180°C

Figure 1. Maximum temperature and average temperature of fuel as a function of time in a DLOFC accident with a scram

The benchmark results for a DLOFC accident simulation with SCRAM performed by several participants from many countries [10] can be seen in Figure 2 and Figure 3. In Figure 2, the maximum fuel temperature is reached after nearly 60 hours with values close to 1700°C. While the average temperature - average fuel after almost 60 hours is about 1150°C.

Figure 2. Maximum fuel temperature of DLOFC accident benchmark results with SCRAM [10]
Figure 3. Average fuel temperature of DLOFC accident benchmark results with SCRAM [10]

4.4 DLOFC Accident without scram

In the event of a DLOFC accident without scram, the reactor remains in operation despite a loss of pressure on the primary system. The same pressure loss scenario as the DLOFC incident with scram is also applied to DLOFC crashes without scram i.e. the process of losing pressure occurs within 13 seconds. The only difference is that the reactor is not scram. After a loss of pressure, the reactor is in subcritical condition. The reactor parameters after the accident can be seen in Table 3.

Table 3. Condition after DLOFC accident without scram

| Parameter          | Value | Unit  |
|--------------------|-------|-------|
| Power              | 1.59  | MW    |
| Inlet temperature  | 586   | °C    |
| Outlet temperature | 750   | °C    |
| Primary pressure   | 1.05  | kg/cm²|
| Primary flow       | 0.26  | kg/s  |

The results for the maximum temperature profile and average temperature of the fuel can be seen in Figure 4. When compared with the results of the study of T. Bismark et al. (Figure 5) [12] and B. Brian, et al [13] (Figure 6), fuel temperature profile after DLOFC accident without SCRAM has the same trend. T. Bismark performs the simulation using the DORT-TD / THERMIX coupling program, while B. Brian uses the DALTON / THERMIX coupling program. Maximum fuel temperature calculated T. Bismark is 1450°C which is reached 25 hours after DLOFC incident. B. Brian's calculations for maximum temperature are about 1600 °C achieved after 40 hours after DLOFC incident. While in this study by using GRSAC, the maximum fuel temperature is 1740°C which is reached about 60 hours after DLOFC accident.
Figure 4. Maximum temperature and average fuel temperature simulated GRSAC program results for DLOFC accident without scram.

Figure 5. Maximum temperature and average fuel temperature simulated DORT-TD / THERMIX program for DLOFC accident without SCRAM [12].
Figure 6. Maximum temperature and average temperature of fuel simulated from DORT-TD / THERMIX program for DLOFC accident without SCRAM [13]

Interesting point in DLOF incident without scram is the change of reactor power. Since the reactor is not scram, there is the possibility of re-occurrence in the reactor when the xenon concentration has been compensated. The GRSAC simulation power change modification profile can be seen in Figure 7. Simulation results with GRSAC, power increase occurred 30 hours after DLOFC incident. When compared with the results of the calculation of B. Brian (Figure 8), criticality returns after 40 hours, whereas the T. Bismark calculation (Figure 9), criticality returns 50 hours after the DLOFC incident.

Figure 7. Reactor power profile after DLOFC accident event without scram simulation result with GRSAC program

Figure 8. Reactor power profile after DLOFC incident without scram simulation result with DALTON / THERMIX program [13]
5. Conclusion

Pressure loss accidents followed by a coolant loss (DLOFC) result in a temperature rise in fuel. The result of DLOFC accident simulation using GRSAC done in this research has a close similarity with benchmark result and other research ever done by using thermohydraulic programs such as DALTON / THERMIX and DORT-TD / THERMIX. The result difference may be due to differences in steady state conditions from each calculation before simulation of transient or accident conditions. In addition, each program also has different modeling and databases. In general it can be concluded that DLOFC accidents on the PBMR reactor resulted in an increase in temperature on fuel, but the maximum temperature reached is still below the specified safety limits. Changes in GRSAC input parameters for HTR-10 or RDE type reactors must continue until they are complete and valid so that an accident simulation for HTR-10 or RDE can be performed.

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