Station Blackout Analysis of HTGR-Type Experimental Power Reactor

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Abstract. The National Nuclear Energy Agency of Indonesia has decided to build an experimental power reactor of high-temperature gas-cooled reactor (HTGR) type located at Puspiptek Complex. The purpose of this project is to demonstrate a small modular nuclear power plant that can be operated safely. One of the reactor safety characteristics is the reliability of the reactor to the station blackout (SBO) event. The event was observed due to relatively high disturbance frequency of electricity network in Indonesia. The PCTRAN-HTR functional simulator code was used to observe fuel and coolant temperature, and coolant pressure during the SBO event. The reactor simulated at 10 MW for 7200 s then the SBO occurred for 1-3 minutes. The analysis result shows that the reactor power decreases automatically as the temperature increase during SBO accident without operator’s active action. The fuel temperature increased by 36.57 °C every minute during SBO and the power decreased by 0.069 MW every °C fuel temperature rise at the condition of anticipated transient without reactor scram. Whilst, the maximum coolant (helium) temperature and pressure are 1004 °C and 9.2 MPa respectively. The maximum fuel temperature is 1282 °C, this value still far below the fuel temperature limiting condition i.e. 1600 °C, its mean that the HTGR has a very good inherent safety system.

1. Introduction
Energy statistics show that electricity demand in Indonesia is increasing every year. The growth rate of electricity demand in 2000 to 2014 is 5.12% per year, and the growth should be balanced with adequate electricity production. The more electricity needed, the more electricity production increase. Power generation in Indonesia mostly uses energy from fossil fuels such as petroleum and coal. The percentage of self-produced electricity energy (including rent) per primary energy type is: natural gas 49,312.48 GWh (28.13%), coal 84,076.12 GWh (47.96%), and oil 26,433.18 GWh (15.08%) [1,2]. Continuous use of these resources causes the supply to run low. In addition, the resulting gas emissions can trigger global warming.

One potential alternative energy source is nuclear energy that can generate enormous energy. In addition, nuclear power plants do not produce air pollution so it is more environmentally friendly. The negative impact of nuclear energy is the presence of radiation produced in the fission process of fuel. However, the radiation can be contained well by a layered defense system in the reactor during normal operation of the reactor.

One of the fourth generation power reactors that have higher inherent safety, more economical, and more efficient power generation is HTGR (high temperature gas cooled reactor). This type of reactor can also be used to produce hydrogen which is needed by the fertilizer industry. HTGR uses helium cooling, developed from GCR (gas cooled reactor) and AGCR (advanced gas cooled reactor)
CO₂-cooled [3,4]. The HTGR reactor is a type of reactor that will be built as an experimental power reactor (EPR) in Serpong. EPR uses uranium fuel and is capable of generating power up to 10 MW thermal (MWt) or equivalent to 3 MW of electricity to supply electricity needs for Puspiptek, Serpong, South Tangerang [5]. Prior to the 10 MW EPR development carried out in the densely populated areas of Serpong, research or testing needs to be done. Lesson learnt from the major accidents that have occurred in previous reactors such as Three Mile Island, Chernobyl, and Fukushima, safety is a major aspect that needs to be considered and studied more deeply so that in the development and operation of EPR can be run as expected.

According to PLN's 2014 statistics, electricity distribution in the Greater Jakarta and Tangerang areas has a significant disturbance index of 2.45 times/customer with a duration of 3.87 hours/customer [1]. This data indicates that in the Puspiptek region has a high probability of losing electricity from the network that could trigger the station blackout. The station blackout is one of the most common trigger events causing damage to the reactor core. The station blackout (SBO) occurs when the reactor has no electricity supply at all. Electrical energy is needed even if the reactor is off to circulate heat on the reactor core. The primary objective of accident management in nuclear power plants is to minimize fission product release into the environment by cooling the core and containment at the same time. However, under extreme condition of extended station black-out (ESBO), as in Fukushima, electric power is totally unavailable to cool the core and the containment. The incident was happened to the Fukushima reactor due to the tsunami which cut off all connections to the source of the power grid and also caused flooding of the emergency generator and made it not functioning. As a result, the pump loses power to circulate water into the reactor so that the reactor core temperature is increased due to the decay heat not being well circulated. Ultimately, the heat causes melting of the reactor core units 1, 2, and 3.

Therefore, the in-depth study on the effect of SBO condition on the EPR or HTGR reactor that will be built in Serpong needs to be done. As a research tool, PCTRAN-HTR is used to simulate reactor behavior and analyze value changes in important parameters when SBO occurs. PCTRAN is a reactor simulation software developed by Micros-Simulation Technology that has validated by FSAR (Final Safety Analysis Report) and uses actual data [6]. The purpose of the analyses presented in this paper is to identify the behavior of important EPR or HTGR parameters in case of total SBO. The PCTRAN-HTR simulator code has also been used to simulate and to analyze the optimum control rods positions in achieving reactor criticality for the continuation of reactor operation [7]. This functional simulator provides a good tool for specialists working in the field HTGR operation and safety.

2. Description of HTGR

The HTGR is a fourth generation power plant developed from GCR (gas cooled reactor) and AGCR (advanced gas cooled reactor). HTGR has many advantages over previous generation reactors such as higher inherent safety, more economical, and more efficient power generation. Heat generated from HTGR can be used for hydrogen production as well as for applications in other fields. HTGR has the potential to become one of the advanced reactors that will continue to be developed. The primary cooling system uses helium as a reactor core coolant. The helium gas flows through the fuel and carries the heat generated by the ²³⁵U fission reaction and is supplied to the steam generator. Then, the water in the secondary cooling system absorbs the heat energy to drive the turbine. This type of reactor is capable of producing temperatures up to 1000 °C that can be used for hydrogen production [4,8,9].

2.1. HTGR reactor fuel

The fuel used in HTGR is in the form of ceramic coated fuel particles (CFP) of tri structural isotropic (TRISO) type, having a diameter of ~ 1 mm. The TRISO fuel consists of a UO₂ fuel kernel enclosed by a porous carbon layer (to release a fission gas fuel), an inner carbon pyrolytic layer (IPyC), silicon carbide (SiC), and an outer pyrolytic carbon layer (OPyC). The TRISO fuel structure is shown in Figure 1 [5]. The TRISO coating can prevent the release of fission products in the fuel because it has a structure that is resistant to very high temperatures. This type of fuel is not damaged when it reaches 2000 °C. Normal HTGR operation is not more than 1250 °C and at the worst accident condition, the fuel temperature is maintained not to exceed 1600 °C, for the HTGR design with helium output.
temperature of 850 °C [9]. The fraction of fuel damage as a function of temperature is shown in Figure 2.

HTGR uses helium gas with a high pressure as a heat transfer medium in the primary system. Helium includes noble gases that are difficult to react and have no heat transfer limit or phase changes. Helium also has a density that has very little impact on reactivity. In Loss of Cooling Accidents (LOCA) the leaking helium in containment does not undergo condensation as in light water reactor (LWR), so the containment can last longer [10]. The HTGR has a relatively low power density so that the changes in temperature occurred in a relatively long time. Damage to the cooling system causes a very slow rise of transient temperature in the reactor core.

2.2. Experimental power reactor (EPR)
The development of nuclear reactor for electricity generation (NPP) in Indonesia until now has not yet been realized. Various issues as constraints of the program, among them are that many people still worried about the safety and security, and not yet convinced that the country has the capability to build and operate the reactor safely. The government through the National Nuclear Energy Agency (BATAN) is initiating for the development of experimental power reactor (EPR) of HTGR type with the main objective is to demonstrate a small NPP which can be operated safely [5].

It is expected by demonstrating the EPR therefore, the trust of the public towards the safety and security in operation of the NPP power reactor and the capability of the country for operating the nuclear reactor would increase. The trust of the public is very important for the success of the plan in the development of a large NPP. The EPR scheme is shown in Figure 3.

3. Material and methods
The loss of off-site power (LOOP) event occurs when all electrical power to the nuclear power plant from the power grid is lost. A station blackout (SBO) is a complete failure of both off-site and on-site
alternating current (AC) power sources [10,11]. The blackout station is a condition when the reactor does not get a power supply at all. The blackout station begins with the LOOP and is followed by the failure of the emergency diesel generator which is the onsite source of electricity [12,13,14]. When a blackout station occurs all systems requiring electrical energy fail to function, including the most important is the malfunction of the reactor coolant circulation pump. This condition may cause the residual heat of the decay to accumulate on the reactor core and cause the fuel temperature to increase.

In 1975, the "Reactor Safety Study" (NUREG-75/140) showed that the SBO could be an important contributor to the total nuclear accident. In addition, the experience gained during operating a nuclear reactor shows that the reliability of emergency AC power source systems both inside and outside the site may still below expectations [15]. The total SBO events are analyzed using PCTRAN-HTR, a computer software created by Micro-Simulation Technology to simulate HTGR operation. The PCTRAN-HTR simulator can be used for calculation of reactor operating parameters until the maximum power of 200 MW. (10 MWe ≤ P ≤ ~60 MWe) such as neutron flux and reactor power distributions, plant efficiency, electric power, load factor, core power density, heat flux, mean burn-up, and excess reactivity. The cooling system parameter can also be calculated such as: flow rate, pressure, gas temperatures at core inlet-outlet, inlet-outlet steam temperatures, steam pressure & temperature at turbine inlet, feed-water temperature, condenser pressure, steam mass flow, gas coolant radioactivity and fuel temperature for various reactor power levels [6]. The reactor parameters can be displayed graphically and numerically and can be saved in output files.

3.1. Mathematical model for helium coolant system
The basic thermal hydraulics of the mathematical model used in PCTRAN-HTR simulator is first-principle in mass and energy balance. This ensures credible and realistic simulations [6]. For a gas-cooled reactor, the primary and secondary helium systems are modelled by two control volumes described by the ideal gas law:

\[ PV = NT \]

where : \( P \) = pressure, \( V \) = volume, a constant for either the primary or secondary gas system, \( N \) = mole number, \( R \) = gas constant, and \( T \) = absolute temperature. The pressure and temperature transient during a transient are then governed by the simple derivative of the above equation and mass and energy input to the system as follows (8):

\[
\frac{dP}{dt} = \frac{dN}{dt} \frac{RT}{M} + NR \frac{dT}{dt} \\
\frac{dN}{dt} = \frac{1}{M_u} (W_{in} - W_{out}) \\
MC_p \frac{dT}{dt} = Q
\]

where, \( M_u \) = molecular weight of the gas, \( W_{in} \) = gas flow influx, \( W_{out} \) = gas flow out-flux, \( C_p \) = specific heat of the gas at constant pressure, and \( M \) = total mass of the gas in the volume.

PCTRAN-HTTR uses a semi-empirical method for reactor coolant flow that encompasses both forced and natural circulation conditions. For forced circulation when the reactor coolant pumps are on, full (volumetric) rated flow is assumed. In the course of pump trip, the flow coasts down exponentially until stable natural circulation is established (3).

\[ W(t) = W_1 + (W_0 - W_1) e^{-\frac{t}{\tau}} \]

where, \( W_0 \) is the nominal rated flow and \( W_1 \) is the eventual natural circulation flow, which is usually a few percent of the nominal. \( \tau \) is the characteristic time. This equation is also used for pump run-out to exceed 100% of its nominal value, i.e., \( W_1 > W_0 \). While, the reactor hot and cold leg temperatures for a HTR are calculated by the heat balance from the reactor core and removal rate by the steam generators at a given loop flow rate as follows:
where $T_{avg}$ is the reactor coolant (RC) average temperature.

### 3.2. Fuel temperature of the reactor core

A simplified model accounting for the temperatures of fuel and cladding has been constructed in PCTRAN-HTTR. This model can simulate: thermal power transmitted into the coolant in contrast to nuclear power generated by the core during normal operation; fuel and cladding heatup during accident conditions. Core thermal power $Q_{MWT}$ is represented by (5)

$$Q_{MWT} = U_F \cdot (T_F - T_{avg})$$

Where $T_F$ is the known average fuel temperature at 100% rated power. The heat transfer coefficient $U_F$ is then calculated such that the core thermal power is equal to the neutron power from the kinetics equation at steady state.

Transient fuel temperature will be calculated by the imbalance between nuclear power and thermal power. The heat transfer coefficient $U_F$ varies with the core flow to the 0.8th power according to Dittus-Boettler correlation during forced circulation and flow coast down. It will settle at a small value for natural circulation. The graphite sleeve and reflector’s temperature is calculated similarly.

The simulated reactor is a 10 MW HTGR, the duration of SBO is varied from 0.5, 1, 1.5, 2, 2.5, 3 minutes on reactor failed and successfully scram. The basic data parameter used in the simulation is presented in Table 1.

#### Table 1. Input basic data

| Parameter                              | Value        |
|----------------------------------------|--------------|
| Rated thermal power per core (MW)      | 10           |
| Rated neutron flux at full power (n/cm$^2$/s) | 3.10$^{14}$  |
| Charging flow (kg/s)                   | 5            |
| Main feed water enthalpy (kW/kJ)       | 600          |
| Total fuel mass (kg)                   | 13333.33     |
| Nominal core helium flow rate (kg/s)   | 6.66         |
| Initial average fuel temperature (°C)  | 1300         |
| Initial gas temperature (°C)           | 878.6        |
| Initial gas pressure (MPa)             | 7.10$^8$     |
| Power range high flux trip (n/cm$^2$/sec) | 4.10$^{15}$  |
| Pressure of steam generator (SG) at zero power (MPa) | 1           |
| Pressure of SG at 100% power (MPa)     | 3.5          |
| Volume of SG (m$^3$)                   | 10           |

### 4. Results and Discussion.

The simulation of the 10 MW HTGR reactor is carried out by operating the reactor for 2 hours (7200 seconds) until the reactor in steady state condition so that all parameters are stable. The SBO condition is simulated from 1 minute up to 3 minutes.

#### 4.1. Reactor fail to scram

Reactor fails to scram is the condition that the reactor still in operating condition when the incident occurred and can be shut down after a while. Simulation of blackout station on a reactor condition fail to scram was done to know how reliable the reactor when the accident occurred. The blackout station causes a loss of helium flow and a secondary coolant so that the reactor experiences a shortage of coolant circulation. The phenomenon that occurs when a station blackout and reactor fails to scram is the rise in fuel temperature and decrease inlet helium temperature. When a blackout station occurs, the helium flow falls sharply until the power source is recovered. During 1 minute of the blackout station, the helium flow decrease reached 3.3 kg/s from the initial of 6.5 kg/s to 3.2 kg/s. After the blackout
station ends, the fuel temperature, helium outlet, and helium inlet return to normal within 5 minutes. Changes in fuel temperature, helium outlet, and helium inlet are shown in Figure 4. At station blackout condition of 1 minute, power decreased 25% or 2.5 MW. The power of the reactor is initially 10 MW turned to 7.5 MW. The decrease is caused by the fuel temperature increase by 61 °C. The power and fuel temperature relation is shown in Figure 5.

The temperature and power profiles for the duration of SBO of 1.5 m, 2 m, and 3 m are similar with the curve profile of Figure 6 and Figure 7. The temperature and power changes for time variation of station blackout are shown in Table 1 and Table 2. The rate of change in fuel temperature is 36.57 °C/min, this is obtained from (Table 2) the average temperature different (ΔT) of fuel divided by the time duration of SBO. The rate of decrease in power of each temperature increase is obtained from (Table 3) the average different (Δ) power divided by ΔT of fuel i.e. 0.069 MW/°C. The increase in fuel temperature causes the reactor power to decrease due to the inherent safety of HTGR i.e. with negative reactivity coefficient of the fuel temperature (Doppler effects) this phenomenon is shown in Figure 7.

### Table 2. Temperature change

| No | SBO (m) | ΔT fuel (°C) | ΔT he-out (°C) | ΔT he-in (°C) |
|----|---------|--------------|----------------|--------------|
| 1  | 0.5     | 34           | 57             | -75          |
| 2  | 1       | 22           | 106            | -128         |
| 3  | 1.5     | 88           | 165            | -171         |
| 4  | 2       | 47           | 203            | -214         |
| 5  | 2.5     | 59           | 250            | -259         |
| 6  | 3       | 71           | 289            | -323         |

### Table 3. Reactor power change

| No | SBO (m) | ΔT fuel (°C) | Δρ Doppler (% dk/k) | Δ power (MW) |
|----|---------|--------------|---------------------|--------------|
| 1  | 0.5     | 34           | -0.05               | -0.05        |
| 2  | 1       | 22           | -0.03               | -2.5         |
| 3  | 1.5     | 88           | -0.12               | -1.8         |
| 4  | 2       | 47           | -0.07               | -4.6         |
| 5  | 2.5     | 59           | -0.08               | -5.5         |
| 6  | 3       | 71           | -0.1                | -6.3         |

4.2. Reactor successfully scram

Reactor successfully scram is the condition that the reactor automatically shut down when the incident occurred. In this condition, the station blackout does not cause a rise in reactor fuel temperature. However, the temperature of the inlet helium increases and the pressure also increases. Although the reactor has undergone a scram, a circulation pump is still required to cool the reactor from the fission products decay heat or residual heat. The decay heat can cause an increase in fuel temperature. The trend of fuel and helium inlet-outlet temperatures for the 3 minutes of SBO incident is shown in Figure 6 and the trend of its pressure change is shown in Figure 7.

The temperature and power profiles for SBO incident duration of 1.5 m, 2 m, and 3 m are similar, such as shown in Figure 6 and Figure 7. It can be seen from Figure 6 and Figure 7 that at a 3 minutes SBO incident the maximum fuel temperature is 1282 °C and the maximum helium gas coolant inlet is 1004 °C. The fuel maximum fuel temperature at this SBO incident is still far belows fuel temperature design limit i.e. 1600 °C such as described in Figure 2 [9]. The results are in accordance with the similar analysis results such as reported by several researchers [16,17,18,19].
5. Conclusion
The station blackout incident on EPR 10 MW of HTGR type which fails to scram causes an increase in fuel temperature with the rate of 36.57 °C/minute. The increase in fuel temperature causes a decrease in reactor power with the rate of 0.069 MW/°C. The maximum coolant temperature and pressure reach 1004 °C and 9.24 MPa respectively, whiles the maximum fuel temperature is 1282 °C. The fuel maximum fuel temperature at this SBO incident is still far bellows fuel temperature design limit of 1600 °C. This result proves that the HTGR has a good inherent safety and the reactor in a safe condition without operator intervention during the SBO event.

6. Acknowledgments
The authors would like to thank the Director of Center for Accelerator Science and Technology Yogyakarta, to the Rector of Polytechnic Institute of Nuclear Technology, as well as to the Head of Reactor Division and all staffs for their supports.

References
[1] PLN. 2015 Statistik PLN (in Indonesian). ISSN: 0852-8179. Jakarta: Sekretariat Perusahaan PT PLN
[2] National Energy Council (DEN). 2016 Indonesia energy outlook 2016. Jakarta: National Energy Council, Secretariat General.
[3] IAEA. 2003 Evaluation of high temperature gas cooled reactor performance: Benchmark analysis related to initial testing of the HTTR and HTR-10, IAEA-TECDOC-1382.
[4] IAEA. 2008 Accident analysis for nuclear power plants with modular high temperature gas cooled reactors, Safety Report Series No.54, Vienna.
[5] BATAN. 2016 Rencana pembangunan RDE, http://www.batan.go.id/index.php/id/reaktor-daya-ekperimental-rde
[6] Micro-Simulation Technology. 2015 PCTRAN-HTR simulator software for PC. New Jersey: Micro-Simulation Technology.
[7] Syarip, Khoirul Anam, Dwi Priyantoro. 2016 Post reactor scram control rods position adjustment analysis for the Indonesian experimental power reactor concept, Ganendra Journal of Nuclear Science and Technology, (Jurnal Iptek Nuklir Ganendra), 19 2 83-93
[8] Hu, S., dkk. 2006 Commissioning and operation experience and safety experiments on HTR-10. Proceedings of the 3rd International Topical Meeting on High Temperature Reactor Technology, D00000052, Johanesburg.
[9] Reitsma, F. 2012 HTGR Safety Design. IAEA Course on High temperature Gas Cooled Reactor Technology. IAEA.
[10] Kadak A.C. 2016 The status of the US high-temperature gas reactors. Engineering 2 119–123.
[11] X. Yan, H. Noguchi, H. Sato, Y. Tachibana, K. Kunitomi, R. Hino. 2014 *A hybrid HTGR system producing electricity, hydrogen and such other products as water demanded in the Middle East*, Nuclear Engineering and Design 271 20–29.

[12] Andrija Volkanovski and Andrej Prošek. 2015 *Delayed station blackout event and nuclear safety*, Science and Technology of Nuclear Installations, Volume 2015, Article ID 192601, 9 pages.

[13] Feng, B. 2014 *Characteristics of helium gas with high temperature and high pressure flowing through a 90-degree elbow*. Journal Power Engineering Volume 2014, Article ID 764283. http://dx.doi.org/10.1155/2014/764283.

[14] Volkanovski, A., Prosek, A. 2011 *Station blackout and nuclear safety*. Proceedings International Conference Nuclear Energy for New Europe.

[15] Baranowsky, P. W. 1988 *Evaluation of station blackout accidents*, Report NUREG-1032. Washington: U.S.A. Nuclear Regulatory Commission.

[16] Jong Woon Park, Wook-Cheol Seol. 2016 *Considerations for severe accident management under extended station blackout conditions in nuclear power plants*, Progress in Nuclear Energy 88 245-256

[17] X. Yan, H. Noguchi, H. Sato, Y. Tachibana, K. Kunitomi, R. Hino. 2014 *A hybrid HTGR system producing electricity, hydrogen and such other products as water demanded in the Middle East*, Nuclear Engineering and Design 271 20–29.

[18] Syarip, Subki, I.R, and Canton, M.H., 1996 *Availability analysis of the AP600 passive core cooling system*, IAEA-TECDOC No-920.

[19] Lommers L.J., Mays B.E., Shahrokhi F. 2014 *Passive heat removal impact on AREVA HTR design*. Nucl. Eng. 271:569–77.