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Safety Philosophy of the GTHTR300

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ABSTRACT

In parallel to successful operation of the Japan's first High Temperature Gas-cooed Reactor, HTTR (High Temperature Engineering Test Reactor), JAERI (Japan Atomic Energy Research Institute) started design and development of a high temperature gas cooled reactor with a gas turbine electric generation system, GTHTR300 (Gas Turbine High Temperature Reactor 300), in April 2001. The GTHTR300 is expected to be deployed in 2010s as a safe and economically competitive electric generation system in Japan.

Unique safety philosophy is proposed for this system. Severe accidents are defined as any conditions beyond design-base accidents, causing core damages with fission product releases to the environment, although all severe accident sequences are very low in probability. The new safety philosophy is to avoid most accidents, and to achieve a probability of severe accidents of 10^{-8}/ry that is at least two orders lower than current reactors. Even in the worst event such as double guillotine break of a primary concentric duct, fuel temperature exceeding its failure limit and excessive fuel oxidation by air ingress can be avoided because of inherent safety features and the passive decay heat removal system. Furthermore, double confinement buildings are enough to keep reactor safety in such accidents. Elimination of a leaktight steel containment vessel is a big economical advantage for this system. Another unique feature is that nearly full-scale worst accident simulation tests can be carried out to obtain licensing before commercial operations because safety assessment by analysis is not usually enough to convince the public and the regulators of trusting this safety concept. In current reactors no accident simulation tests are carried out before commercial operations although inspection and performance tests in normal condition are conducted.

This paper describes the safety philosophy together with the outline of the design features of the GTHTR300, and the results of preliminary safety evaluation of the depressurization accident and reactivity insertion accident. The depressurization accident initiated by double guillotine break of a primary concentric duct is thought to be the severest event in the GTHTR300. In this evaluation, it was confirmed that the fuel temperature and amount of fuel oxidation were below the limit.

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Key words HTGR, HTGR, Gas Turbine, Safety, Safety criteria, reactivity insertion, depressurization accident

INTRODUCTION

The HTGR (High Temperature Gas Cooled Reactor) is expected to be a future energy source for wide variety of process heat applications such as gas turbine, hydrogen production, etc. JAERI has been developing the HTTR[1] since 1960s. The full power operation with its thermal power of 30MW and outlet gas temperature of 850• was attained in December 2001, and operational licensing for a rated operation was given from the MEXT (Ministry of Education, Culture, Sports, Science and Technology of Japan) in March 2002. Safety demonstration tests to confirm the HTGR safety will be performed until a hydrogen production test section will be connected with the secondary cooling system of the HTTR.

JAERI also has been developing various heat application systems. The electric generation by a helium gas turbine using the heat from the HTGR has high potential as an efficient energy supply system. Therefore, JAERI started design and development of GTHTR300. Economical target of this system is the electricity cost of 4 Yen/kWh taking advantage of inherent safety features of the HTGR and adopting unique design originalities. The basic design phase consisting of system and component design, safety evaluation and economical assessment will be finished by the end of March 2004. Design modification will be conducted from 2004 to 2007 after a design review by utilities, and the basic design and development of the GTHTR300 including R&D for a gas turbine system will be finished by the end of March 2008.

The design philosophy of the GTHTR300 is SECO (Simplicity, Economic Competitiveness and Originality). Simple design based on existing technologies and operational experience is adopted to enhance economic competitiveness. Also, original design concept different from that of GT-MHR[2] and PBMR[3] was proposed. Major features on reactor systems of the GTHTR300 are horizontal arrangement of a turbocompressor unit, and separation of a power conversion vessel (PCV) and heat exchanger vessel (HEV). Most of the conventional fossil turbocompressor units in Japan are mounted horizontally for easy operation and maintenance. Due to the horizontal arrangement, design, operational and maintenance experience obtained from conventional turbocompressor units are used for the GTHTR300. Regarding the safety system, a Reactivity Cavity Cooling System (RCCS) modified from a Vessel Cooling System (VCS) in the HTTR is adopted to avoid further R&Ds. Except above concept and systems, many technologies developed for the HTTR and conventional turbocompressor units are used for the GTHTR300.

Safety philosophy is of prime importance to keep safety but avoid plant complexity for the GTHTR300. Safety philosophy of the HTTR is partly available for the GTHTR300. However, it was not suitable for a commercial reactor aiming at high economical target. The safety philosophy for the GTHTR300 was established to meet safety requirements without losing economical competitiveness.

OUTLINE OF GTHTR300

Figure 1 shows the conceptual view of the GTHTR300, and Table 1 shows the major specification of the GTHTR300. The GTHTR300 is a helium cooled and graphite moderated HTGR with the outlet helium gas temperature of 850• and the thermal power of 600MW. The outlet temperature was determined as a trade off of thermal efficiency and system complexity. For example, turbine blade cooling is not necessary in the case of outlet temperature of 850•. Avoidance of sophisticated blade forced cooling greatly reduces risk of turbine malfunction and increases reliability although the plant thermal efficiency decreases about 3-4%. Thermal power of 600MW was determined in order to keep the fuel temperature within the limit of 1600• even in the worst accident that no forced cooling is expected. The turbocompressor unit is horizontal located in the rector building, and heat exchanger units and turbocompressor unit are separately installed in the PCV and HEV respectively. Due to the arrangement, maintenance scheme is easy because the maintenance of the turbocompressor and heat exchangers can be simultaneously conducted without any interference.

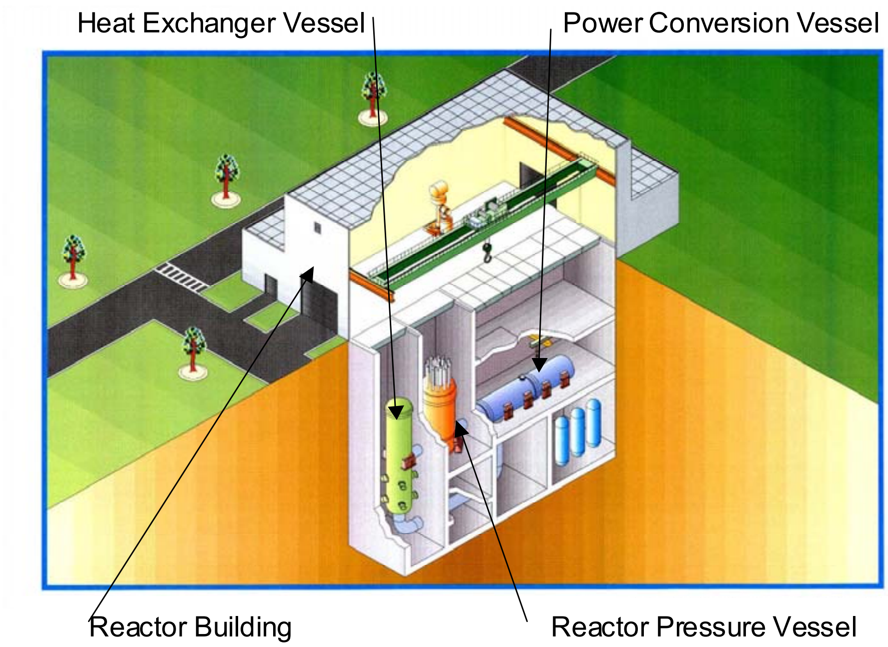

Figure 1 General overview of GTHTR300

The reactor core design is based on that of the HTTR so as to reduce R&D needs for the new system. The pin-in-block type fuel blocks are stacked annularly in the core. Accordingly, fuel design and fabrication technology are almost the same as that of the HTTR except the thickness of the coating layer. It was increased to improve retaining performance of fission products in high burnup condition.

Table 1 Major specification of the GTHTR300

Thermal power	600 MW
Outlet helium/Inlet helium gas temperature	850•/587•
Gas turbine inlet pressure	7 MPa
Gas turbine mass flow rate	439 kg/s
Core height	8 m
Inner and outer diameter of core	3.6/5.5 m
Fuel enrichment	14 %
Average power density	5.8 W/m^3
RPV diameter	7.6 m
PCU diameter	5.7 m,
HEX diameter	5.8 m
Plant efficiency	46%

Safety related systems such as RCCS and confinement structure are also radical in the GTHTR300. The RCCS consisting of air-cooling panels with small fins is installed around the Reactor Pressure Vessel (RPV). The air inside the panels are passively circulated. In the case that forced core cooling is not expected, the decay heat and residual heat of the core can be removed by radiation from the RPV surface to the air-cooling panels of the RCCS. The confinement structure does not consist of a steel containment. However, to prevent air ingress from atmosphere, a double confinement structure was proposed and designed. Figure 2 shows the concept of the double confinement structure. In the case of the depressurization accident, the double confinement makes a following role; (1) Helium gas escaped from the primary circuit pressurizes a belowground confinement. (2) A safety valve between the belowground and aboveground confinement opens because of the internal pressure increase. (3) The internal pressure in the aboveground confinement increases, and the helium gas is released into the atmosphere through another safety valve at the roof. (4) After the helium gas release, the internal pressure of the belowground confinement, the aboveground confinement and the atmospheric pressure equilibrates, and the safety valves close. In the single confinement, air ingresses into the confinement due to the density difference between the atmosphere and internal gases. On the other hand, in the double confinements, soil around the belowground confinement limits the air ingress. Also, since all hatches and entrances of the building are attached to the aboveground confinement, air leakage through those structures in the belowground confinement is prevented.

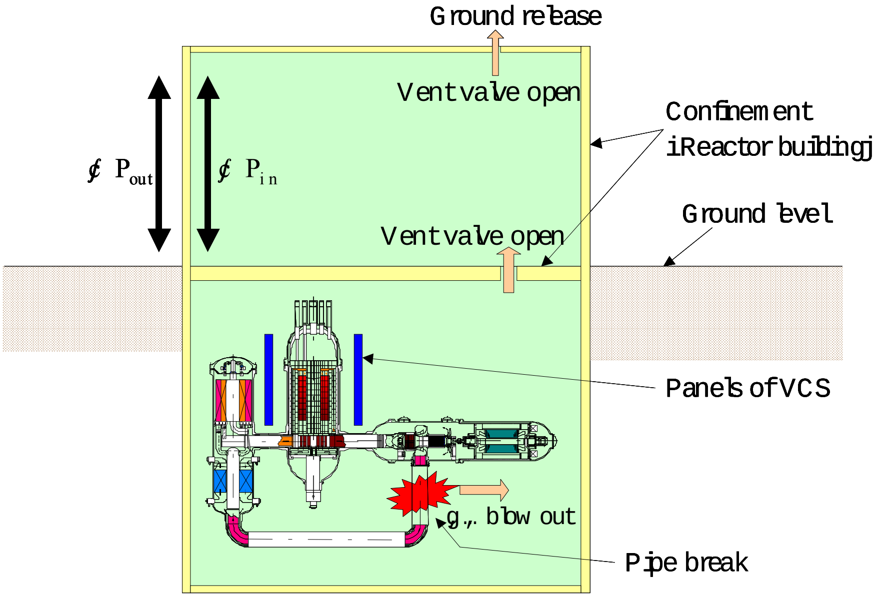

Figure 2 Event scenario during depressurization accident

SAFETY PHILOSOPHY

Defense-in-Depth and severe accident free

Defense-in-Depth is a basic philosophy for the GTHTR300 as well as a LWR. Various layers of requirement are used to keep safety. However, major differences of the safety philosophy between the GTHTR300 and the current LWR are the followings. The LWR uses highly reliable, redundant and diverse passive or active safety layers. On the other hand, the GTHTR300 safety shall be kept due to inherent safety characteristics and potentially safe components.

Severe accidents are defined as any conditions beyond design-base accidents, causing core damages with fission product releases to the environment, although all severe accident sequences are very low in probability. The new safety philosophy is to avoid most accidents, and to achieve a probability of severe accidents at least lower than 10-8/ry in an internal event. That is two orders lower than current reactors. Even in the worst event, fuel temperature exceeding its failure limit and excessive fuel oxidation by air ingress can be avoided because of inherent safety features and the passive decay heat removal system. The severe accident caused by the external event is prevented due to the same procedure as that of a new generation LWR.

Demonstrable safety

Nearly full-scale worst accident simulation tests can be carried out to obtain licensing before commercial operations because safety assessment by analysis is not usually enough to convince the public and the regulators of trusting this safety concept. In current reactors no accident simulation tests are carried out before commercial operations although inspection and performance tests in normal condition are conducted. On the other hand, safety demonstration by accident simulation tests can, and shall be, requisite to obtain licensing in the GTHTR300.

Mechanistic source term

Mechanistic source term is used to estimate radionuclide releases for plant siting evaluation instead of non-mechanistic source term based on AEC document TID-14844, Japanese LWR or HTTR safety evaluation guideline [4].

Initial failure of coated fuel particles in the HTTR in manufacturing is only 8×10^{-5} comparing with 10^{-2} in design, and no apparent failure was found in continuous irradiation tests up to 6.5% FIMA at Japan Material Testing Reactor (JMTR). A post irradiation test is also planed to be carried out next year. In addition to these tests, data for long term integrity of the fuel, lift off and plate out behavior will be accumulated in the HTTR operation. The full power operation of the HTTR was already finished, and no additional failure was found evidently. These are the reason why the mechanistic source term can be used for the plant siting evaluation.

Double confinement and no containment vessel

When the above mentioned mechanistic source term is used for the plant siting evaluation, the effective dose equivalent to whole body in the worst event can meet the dose guideline without the containment vessel. No containment vessel is necessary in the GTHTR300 due to salient fuel performance, and resuspension and transport phenomena pertaining to the radionuclide within a primary circuit. However, in order to limit the air ingress into the core and fuel oxidation, the double confinement is used in this system.

No need for offsite emergency evacuation and no damage on all offsite assets

Offsite emergency evacuation is not necessary in the worst event selected for the plant siting evaluation. Furthermore, all offsite assets are kept intact and ensured.

PSA and Event selections for the safety evaluation

The safety evaluation of the GTHTR300 has been made considering its inherent safety characteristics and salient engineering features of this system. The classification of the events to be evaluated is based on the HTTR and LWR safety evaluation guideline [4]. In LWR and HTTR safety evaluations, the Anticipated Operation Occurrence (AOO) is defined as the off-normal events with its frequency of roughly lower than approximately 10^{-2}/ry, and the accident is defined as that with its frequency of lower than approximately 10^{-4}/ry. The deterministic evaluation will be carried out to these AOOs and accidents. On the other hand, in the GTHTR300 safety evaluation, the accident is defined as the events with its frequency in the range from 10^{-2} /ry to $10^{-8/}$ry. The deterministic evaluation shall be made for these accidents. Full-scale PSA will not be forced for designing the GTHTR300. Full scale probabilistic evaluation is performed for reference.

SAFETY EVALUATION OF GTHTR300

Acceptance criteria

Acceptance criteria for the GTHTR300 were determined based on those of the HTTR. Regarding the fuel and core damage criteria, the basically same criteria were used as those of the HTTR. Table 2 shows the acceptance criteria for the GTHTR300.

Table 2 Acceptance criteria for fuel in Anticipated Operational Occurrence and Accident

Anticipated Operational Occurrence	The maximum fuel temperature < 1600 •
Accident	No severe damage in core

Acceptance criteria for the primary boundary and turbocompressor unit will be studied next phase of the design.

Selection of the events

Off-normal events to be postulated as AOOs and accidents were selected considering its frequency of occurrence and based on the investigation of main causes that affect each item of the acceptance criteria identified for the GTHTR300, that is (a) fuel temperature, (b) core damage, (c) pressure at the primary boundary , (d) missile damage from the turbocompressor unit, (f) pressure inside the confinement.

A major accident and hypothetical accident are selected and evaluated to endure the safety of the public in the case of serious accidents.. The depressurization accident initiated by a break of the concentric cross duct between the RPV and PCV, or the reactivity insertion accident following the depressurization initiated by a stand pipe rupture are the severest accident in the GTHTR300. The major and hypothetical accident will be determined after the preliminary evaluation of both events.

In the safety evaluation of the HTTR, the same source term as that of the LWR was used in the major and hypothetical because no experience for HTGRs had been accumulated in Japan although safety authority admitted the safety advantage of the HTTR theoretically and technically. After the successful operation and safety demonstration tests of the HTTR, mechanistic source term was used in the major and hypothetical accidents.

Preliminary results of safety evaluation

In the final safety evaluation, the evaluation of all events selected in each evaluation category shall be carried out. But, first, we preliminary evaluate the following two events, the depressurization accident initiated by the break of the concentric hot gas duct and the reactivity insertion accident initiated by a stand pipe rupture. These two events represent the severest effect on the reactor system

(1)Depressurization accident

After the concentric pipe rupture between the RPV and PCV, the fuel temperature increases due to the loss of the forced cooling of the core though the reactor is shut down by the detection on the decrease of primary flowrate. The RCCS can remove the residual heat of the core from the RPV to the cooling panel of the RCCS by mainly radiation. Then, primary coolant helium gas including fission products blows out to atmosphere. Shearing force produced by the helium gas lifts off plate-out fission products on the inner surface of the primary pipes, turbine blades and a heat exchanger core. Those fission products detached from the primary circuit are released from a stack to the environment. After the complete release of the helium gas, air ingress into the core starts. The air ingresses into the core by diffusion until the amount of air reaches the point that makes the driving force of natural circulation enough to induce the air into the core. However, the core temperature decreases below the oxidation reaction temperature and the oxidation of the core is limited.

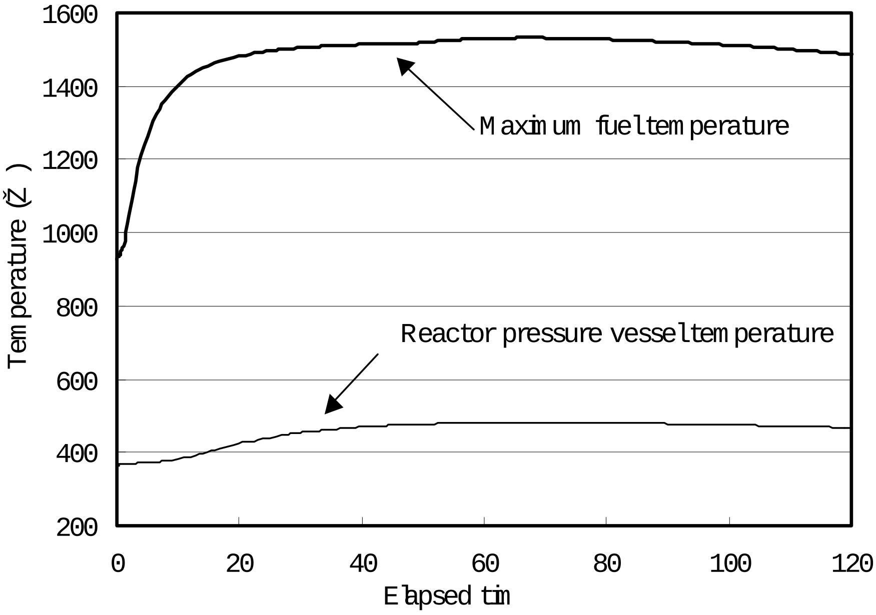

Figure 3 Reactor transient during depressurization accident

Temperature transient in the depressurization accident was evaluated by TAC-BLOOST code[5]. The code was verified before the safety evaluation of the HTTR. Figure 3 shows the maximum fuel temperature and power during the accident. The temperature does not exceed 1600• during the accident. The results proved that the RCCS can successfully cool the RPV as well that internal graphite structures absorb the decay heat.

The double confinement can limit the fresh air ingress from atmosphere. The oxidation evaluation for the fuel will be carried out next year.

(2)Reactivity insertion accident

The GTHTR300 has 30 standpipes containing a pair of control rods. Each pair of controls has 0.5%dK/K of control rod worth during the rated operation. In this event, one out of 30 standpipes is assumed to be ruptured. The reactivity is inserted by the control rod withdrawal after the stand pipe rupture. The fuel temperature increases due to the reactivity insertion into the core. Then, the helium gas release through the breaking hole starts, and eventually replacement of helium and air occurs. However, after the replacement of air and helium gas, the further air ingress

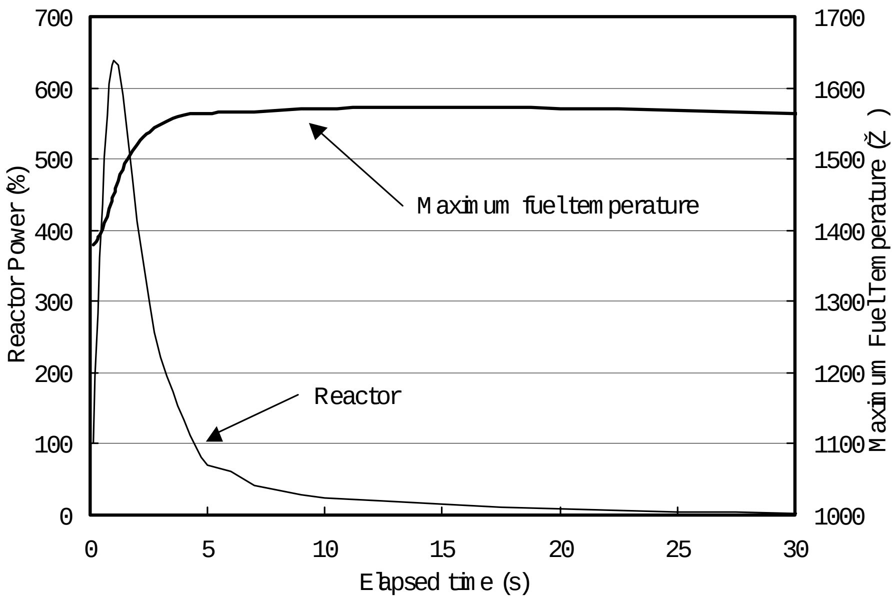

Figure 4 Reactor transient during reactivity insertion accident

is prevented because of no driving force. Fission products release by lift-off is limited comparing with that of the depressurization accident because of the lower shearing force. The long-term temperature transients of the core are almost the same as that of the depressurization accident.

The transient behavior of the reactivity insertion accident was also evaluated by TAC-BLOOST code. Figure 4 shows the maximum fuel temperature and reactor power after the control rod withdrawal. The reactor power rapidly increases and peaks over 600 % at a few second. However, the reactor power rapidly decreases due to Doppler effect of the fuel. The power over 100 % continues only about 5 seconds and the thermal power accumulated in the core is limited. That is the reason why the maximum fuel temperature is blow the limit

The double confinement limits the fresh air ingress from atmosphere. The oxidation of the fuels will be carried out next year..

CONCLUSION

(1) The following safety philosophy for the GTHR300 was proposed.
   - Severe accident is prevented by complete passive system
   - Nearly full scale demonstration test is performed before the operation.
   - Deterministic safety evaluation is performed if the frequency of evaluated events is higher than 10^{-8}/.ry
   - Full scale probabilistic evaluation is performed for reference because the safety of the system is evaluated deterministically.
   - Mechanistic source considering the operational experience of the HTTR is used.

(2) Preliminary safety evaluation of the GTHTR300 was carried out. It is confirmed that the fuel temperature during the depressurization accident and reactivity insertion accident was below the temperature limit of 1600•.

(3) The double confinement can limit fresh air ingress into the core and prevent the fuel oxidation.

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