Feasibility Studies on Commercialized Fast Breeder Reactor System (2) Gas Cooled High Temperature FBR

Yoshihiro Kiso[1)], Jun Kobayashi[1)], Masanori Kida[1)], Masashi Nomura[2)], Masakazu Ichimiya[1)]

1) System Engineering Technology Division, OEC, Japan Nuclear Cycle Development Institute, Oarai, Japan
2) The Japan Atomic Power Company, Tokyo, Japan

ABSTRACT

Japan Nuclear Cycle Development Institute (JNC) and Electric Utilities have been conducting Feasibility Studies on Commercialized FBR Systems since July 1999 under the cooperation Agreement. In that studies the preliminary concepts of various types of fast breeder reactors such as sodium cooled, heavy metal cooled and gas cooled reactors etc. have been designed and evaluated. For the gas cooled reactors, the preliminary design concepts of all the possible combination of carbon dioxide and helium coolants, steam turbine and gas turbine power generation cycles, sealed pin and coated particle fuels have been examined incorporating many innovative technologies. High temperature FBR utilizing gas turbine concept, one of the preliminary design concepts of gas cooled FBRs, accomplishes high plant cycle efficiency (47%) by direct gas turbine cycle with high reactor inlet/outlet temperature (460°C/850°C). The reactor also accomplishes core melt proof safety design mainly by its low core power density (30MW/m^3). The reactor core does not melt even in the hypothetical depressurized and without-scram severe accident by means of passive shutdown equipment and natural circulation. Fuel burnup and breeding ratio of the reactor are 95GWd/t and 1.09, respectively.

INTRODUCTION

JNC and Electric Utilities have been conducting Feasibility Studies on Commercialized FBR Systems since July 1999. This research program aims to clarify the perspectives for commercialized fast reactor system by making the maximum use of its primary advantages in order to achieve the economic competitiveness of fast reactor cycle system to that of LWRs and other base power sources. For this purpose, during the first phase (Phase I study), a wide range of technologies using innovative technologies are reviewed and evaluated. In the Phase I study a gas cooled FBR has been investigated.

The classification of gas cooled FBR concepts in Phase I study are shown in Fig. 1. Studied coolants are carbon dioxide

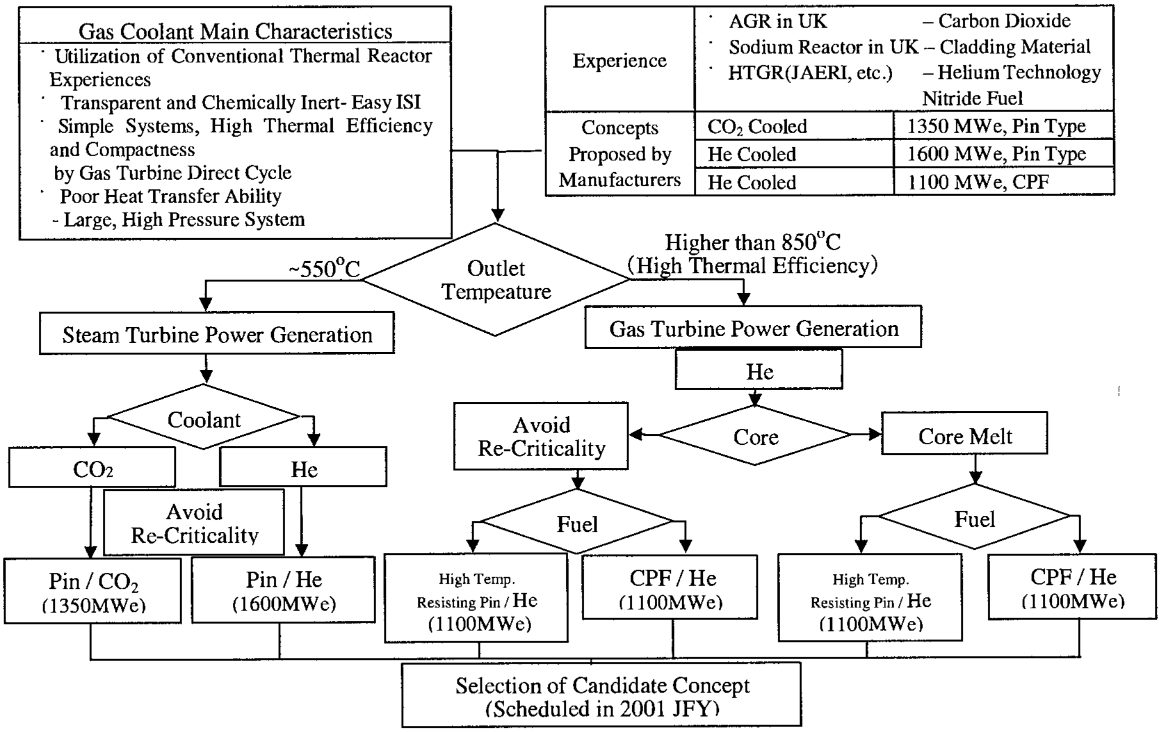


Fig.1 Gas Cooled FBR Concepts

(CO_2) and helium (He) gases, those gases are utilized for many thermal nuclear reactors. From the view point of electric power generation cycle, reactors are classified into steam turbine cycle and gas turbine cycle concepts, of which reactor outlet temperatures are about 550°C and 850°C respectively. The steam turbine cycle power generation concepts aim at the elimination of R&D works applying conventional technologies as much as possible. The gas turbine cycle power generation concepts aim at high thermal efficiency and system simplification by direct coupling with reactors. As for fuel type, sealed pin and coated particle fuel concepts have been studied. The coated particle fuel (CPF) is a sphere in diameter 1 to 2mm of which fuel kernel is coated by high temperature resisting ceramics. CPF experiences have been accumulated in many high temperature thermal gas cooled reactors. The CPFs were not used for the steam turbine cycle because the ceramics coatings work as a neutron moderator and fast reactor nuclear performance such as burnup or breeding ratio decreases. The CPFs should be used at high temperature because high thermal efficiency is expected to overcome the defect.

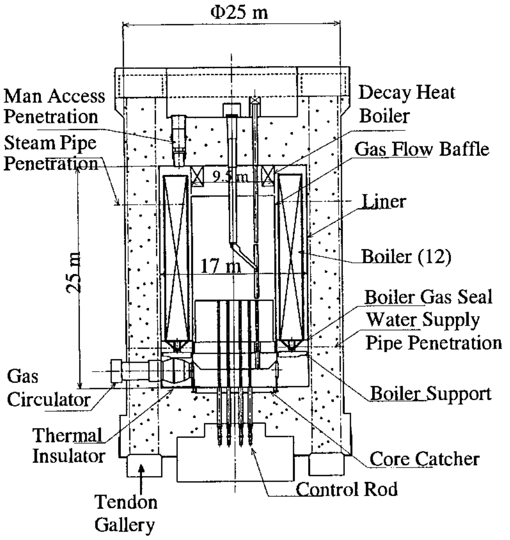
The steam turbine cycle can be combined with both carbon dioxide and helium gas coolants. In Phase I study, preliminary concepts of sealed pin type and carbon dioxide cooled FBR have been designed and evaluated.

The gas turbine cycle is operated at high temperatures. There are experiences for CO_2 gas to be used for AGRs at the reactor outlet temperature as high as about 650°C. However the high temperature corrosion characteristics of CO_2 gas above that temperature has not been investigated. Therefore the gas turbine cycle was combined only with He gas. The gas turbine cycle power generation concepts are further classified into the two types, Core Catcher Type (CCT) and Core Melt Proof Type (CMPT) considering the countermeasures to core disruptive accident (CDA). The melt core during CDA is cooled and the re-criticality is avoided by a core catcher in CCT reactors, while in CMPT reactors the core does not melt and re-criticality is avoided. For the gas turbine cycle both the sealed pin fuel and the CPF can be applied.

In this paper the preliminary plant design concept of carbon dioxide cooled and steam turbine cycle FBR is reviewed briefly and that of CMPT/CPF helium cooled reactor utilizing the gas turbine is explained in detail, then the safety analysis result of CMPT/CPF helium cooled reactor is described. Lastly sealed pin type and helium cooled FBR is explained briefly.

CARBON DIOXIDE COOLED STEAM CYCLE FBR

The preliminary design concept and main characteristics of the CO_2 cooled FBR plant is shown in Fig. 2.



Electric Power	1370 MWe
Thermal Power	3600 MWt
Helium Temperature (In/Out)	266°C / 530°C
Helium Flow Rate	11900 kg/s
Helium Pressure	4.2 MPa
Primary Circuit Loops	4 loops
Fuel Type	Sealed Pin Fuel
Average Fuel Burnup	155 GWd/t
Breeding Ratio (BR)	1.195
Inner / Outer Core BR	0.51 / 0.212
Radial / Axial Blanket BR	0.176 / 0.297
Core Power Density	255 MW/m^3 (Av.)
Reactor Pressure Vessel	Prestressed Concrete
Decay Heat Removal System	4 systems
Reactor Containment	SCCV
Equivalent Core Diameter	5.9 m
Core Height	1.2 m
Axial Blanket (Upper/Lower)	0.4 m / 0.4m
Fuel Cycle Length	730 days
Fuel Batch Number	5
Pu Enrichment (In/Out)	19.8 / 28.0 wt%
Doubling Time	51 years

Fig. 2 CO_2 Cooled Steam Cycle FBR

The thermal power and the electric power of the plant are 3600MWt and 1370MWe. The components of the reactor primary circuits, a core, reactor internals, 12 boilers and 8 gas circulators are housed in a prestressed concrete reactor vessel (PCRV) and the primary pressure boundary of the plant is bounded by the PCRV. The outer diameter of the PCRV is 25m. As one of the countermeasures to depressurized accident, the severest design basis accident for gas cooled reactors, flow restrictors are installed at the boiler tube PCRV penetrations considering the pipe breaks. The flow restrictors limit coolant leak areas. In addition to normal main and back up shutdown systems, self-actuating safety shutdown systems (SASS) are also installed in order to increase the reliability of shutdown. The rods of the SASS are inserted passively. If core melt occurs in CDA, the core catcher at the bottom of the PCRV would be able to cool the melt and avoids re-criticality. The average burnup and the breeding ratio of the core are 155GWd/t and 1.20 for mixed oxide fuel and 159GWd/t and 1.38 for mixed nitride fuel.

HELIUM COOLED GAS TURBINE FBR (COATED PARTICLE FUEL)

This reactor consists of high temperature resisting coated particle fuels and reactor internals, which in combination with gas turbine cycle enables high plant efficiency and the removal of intermediate heat transfer systems. That makes the plant more compact and economically attractive.

The most valuable feature aimed at by the design is the achievement of a core melt proof reactor safety concept. The goal of the safety concept is explained as follows.

Core melt and re-criticality should be avoided without any active component actuations even under depressurized accident conditions, namely, coolable geometries of the core should be kept and the core should be cooled only with passive components and natural circulations in the sequence of (depressurized accident + without scram + without active component actuation). (FP release from the core is allowed in CDA, however it's retained in a containment.)

Outline of the plant

Plant main characteristics are shown in Table 1 and a plant system concept is shown in Fig.3. The thermal power is 2400MWt and the electric power is 1120MWe. A reactor pressure vessel (RPV) and four power conversion vessels are installed in the containment. A gas turbine power generation system is housed in a power conversion vessel (PCV). Coated particle fuel is employed. The CPFs are cooled directly by helium coolant without being distributed in matrix. The direct cooling of the CPFs achieves a good coolablity performance and a large fuel to core volume ratio. The reactor inlet/outlet temperature is $460^{\circ}C/850^{\circ}C$ as high as HTR. Compared to sodium-cooled reactors, intermediate heat transfer systems and sodium treatment systems etc. are not necessary and the number of systems are reduced. The power conversion unit fabricated in module improves manufacturability in a factory and installation works at site. He gas is chemically inert and has good compatibility with fuels and structures even in the high temperature range and is not activated by fast neutron radiations. He gas can eliminate sodium-water reaction and can make inspections and surveillances easy because of its transparency.

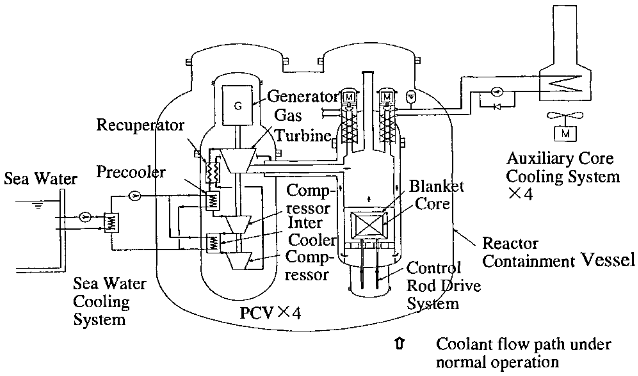


Fig. 3 Plant System Concept

Table 1 Plant Main Characteristics

Electric Power	1120 MWe
Thermal Power	2400 MWt
Helium Temperature (In/Out)	$460^{\circ}C$ / $850^{\circ}C$
Helium Flow Rate	4262 ton/h
Helium Pressure	6 MPa
Primary Circuit Loops	4 loops
Fuel Type	Coated Particle Fuel
Average Fuel Burnup	95 GWd/t
Breeding Ratio	1.09
Core Power Density	30 MW/m^3 (Av.)
Reactor Pressure Vessel	Steel (SA533)
Core Auxiliary Cooling System	Direct Core Cooling 50%(FC) x 4
Reactor Containment	Steel (SPV490)

Core

Core main characteristics are shown in Table 2 and the core structure is shown in Fig.4. The height and the equivalent diameter of the active core is 3.2m and 5.6m respectively. The core consists of 438 core fuel assemblies, 27 main and back up control rods and 4 passive control shutdown equipments.

Mixed nitride fuel is adopted as fuel material. The core burnup is 95GWd/t and the breeding ratio is 1.09 (the number of radial blanket was reduced as small as possible in order to reduce the recycle burden of the radial blanket). As explained later, the CPF consists of a fuel kernel and coated layers. The fuel inventory of the CPFs is restricted by the CPF diameter and the coated layer thickness. The CPF diameter is limited by manufacturing ability. The coated layer thickness is determined so as to ensure the CPF integrity. Therefore the plutonium enrichment that expands the burnup, and the quantity of uranium 238 that raises the breeding ratio cannot be increased simultaneously. When the burnup is raised to 150GWd/t, the increase of coated layer thickness and the decrease of uranium 238 amount make the breeding ratio much smaller than 1.09.

The neutron spectrum of the core is softer compared to general sodium-cooled FBRs because of its material compositions of the coating layers and the structures. That improves a Doppler reactivity coefficient. The core power density $30MW/m^3$ is the requirement of the safety analysis.

The reactor power is determined based on the diameter of the steel reactor pressure vessel and the core power density.

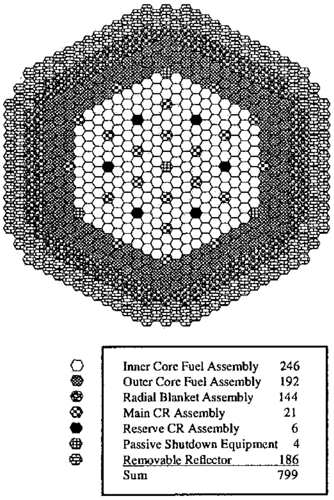


Fig. 4 Core Structure

Table 2 Reactor Core Characteristics

Equivalent Core Diameter	5.62 m
Core Height	3.2 m
Axial Blanket (Upper/Lower)	0.4 m / 0.4m
Fuel Cycle Length	18.7 EFPM
Fuel Batch Number	7
Pu Enrichment (Inner)	20.5 wt%
Pu Enrichment (Outer)	27.0 wt%
Peak Fast Neutron Fluence	2.5×10^{23}n/cm^2
Breeding Ratio (BR)	1.09
Inner / Outer Core BR	0.459 / 0.225
Radial / Axial Blanket BR	0.275 / 0.135
Doubling Time	117 years
Doppler Coefficient (Tdk/dT)	-0.0092
Depressurization Reactivity	2.5$

Fuel and fuel assemblies

The structure and the dimensions of the CPF are shown in Fig.5. The pyrocarbon layer used for HTR Tri-Isotropic CPF cannot maintain its integrity under the fast neutron fluence of this core. That would probably break.[1] The CPF coating material is now studied further. For this design concept the most probable candidate, TiN was selected as a reference coating material. Mixed nitride fuel is employed as the fuel kernel material considering the increase of the fuel inventory and the core fuel performance such as the reactivity and the breeding ratio etc.

The CPFs have been used by being distributed in graphite matrices as pellets or pebble balls for HTR. However in this design the CPFs are directly cooled in order to increase the fuel to core volume ratio and heat transfer areas.

The fuel assembly concept and coolant flow paths are shown in Fig.6. The fuel assembly consists of a cylinder rod element called fuel compartment, axial blankets and shields at the upper and lower part of the rod. The fuel compartment consists of an inner and an outer cylinder and the CPFs are packed between these two cylinders. The two cylinders are made of SiC/SiC composite material, which is the fabrics weaved by SiC fibers and coated by SiC thin layer.

Helium coolant flows in from the bottom of the fuel compartment and flows up axially in the inner side of the inner cylinder, and flows radially through the porous inner cylinder, CPF packed beds, the outer porous cylinder and flows up to an upper plenum. The radial flow in the CPF packed beds with a small axial flow rate under normal and accident natural circulation conditions is realized by the larger pressure loss coefficient (namely small porous areas) of the inner cylinders compared to the CPF packed beds and the outer cylinders.

The fuel assembly structure is designed so as to maintain its integrity under high temperature accident conditions by the ceramics structures and obtain the smallest total pressure loss (about 0.4MPa) by short flow paths. The small total pressure loss contributes to the plant efficiency and secures natural circulation flow rates.

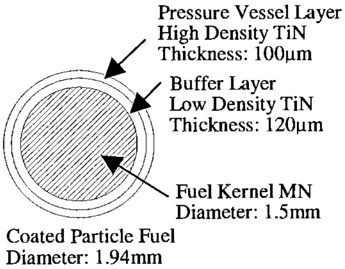


Fig. 5 Coated Particle Fuel

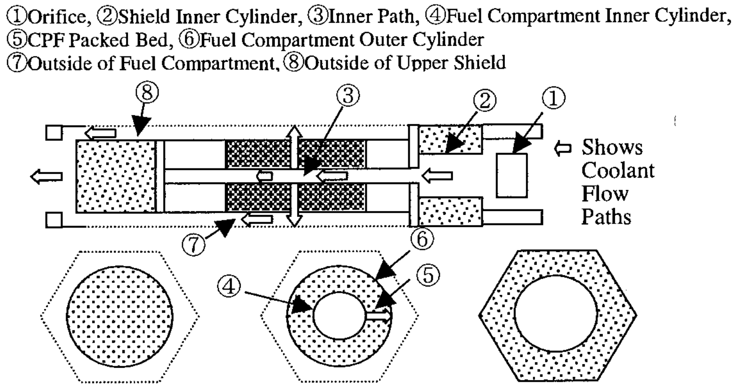


Fig. 6 Fuel Assembly Concept and Coolant Flow Path

Reactor structure

A reactor structure concept is shown in Fig.7. The reactor consists of double containments, the RPV and an inner containment that form a coolant inlet flow path. 4 PCVs are connected to the RPV by cross ducts (annular pipes). The nozzles protruded from the RPV at each 90° angle support the RPV. At the upper head of the RPV, auxiliary core cooling system heat exchangers(ACCS HXs) and standpipes for fuel exchange are installed and at the lower head of the RPV, control rod drive assemblies are installed.

Heat treated Mn-Mo-Ni steel, which is generally used for PWR, is employed for the RPV considering a cost reduction. Thermal insulation and neutron shield layers are installed at the inner side of the RPV. The RPV is cooled by the atmosphere cooling system of the reactor containment. The inner diameter of the RPV is limited to about 10m, which is determined so that the RPV can be manufactured with slightly modified manufacturing facilities and can be transported with conventional measures.

The core is supported by core supporting structures and encircled by the graphite blocks in radial direction.

Helium coolant flows in through outer pipes of cross ducts, flows down between the RPV and the inner containment, flows through the core and flows out to gas turbine power generating systems through the inner pipes of cross ducts.

The inner containment vessel is made of modified 9Cr steel. In order to thermally insulate inlet coolant from outlet one, a thermal insulator is installed at the inside of the containment vessel. Kaowool is considered as the candidate insulator material. B_4C layer is also installed under the thermal insulator to shield fast neutron streaming from the core.

The flow restrictor concept is shown in Fig.8. The flow restrictors are installed encircling the cross ducts. That limit the break areas and the depressurization speed of primary circuits when the guillotine pipe break of cross ducts occurs. The leak area, namely the gap areas between cross ducts and flow restrictors, is requested to be less than $50cm^2$ based on the safety analysis results.

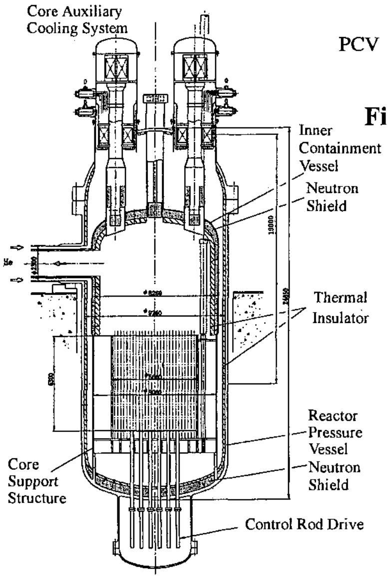


Fig. 7 Reactor Internal Structures

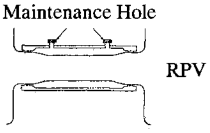


Fig. 8 Flow Restrictor Concept

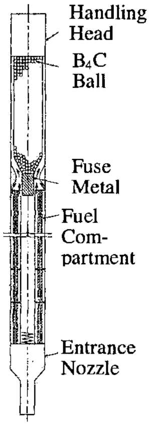


Fig. 9 Passive Shutdown Equipment

Reactor shutdown system

Reactor shutdown system consists of a reactor control & shutdown system (main, back up shutdown rods) and passive shutdown equipments. The control and shutdown rods are inserted into the core from the bottom because the temperature of the upper plenum atmosphere is very high (850°C) under normal and accident conditions and there is little space for the control rods at the upper head of the RPV, where ACCS HXs and standpipes for fuel exchange are installed.

The concept of the passive shutdown equipment has been studying. One of the concepts is shown in Fig.9, which uses a fuse metal for insertion mechanism and boron balls as control elements. An electro magnetic method utilizing the curie point is also studied. The time period necessary to insert the control elements in severe accidents is much longer (about 5~10min.) than sodium-cooled reactors (a few seconds). That much longer period of time is sufficient to accumulate heat for actuating the self-actuation system (such as fuse metal) although the heat transfer of gases are much smaller than liquid metals.

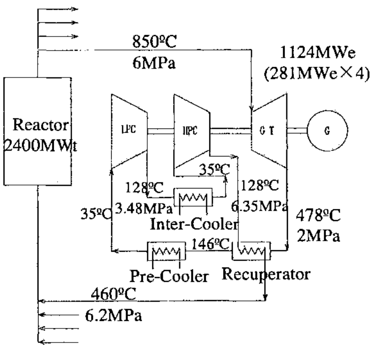


Fig. 10 Primary Circuit

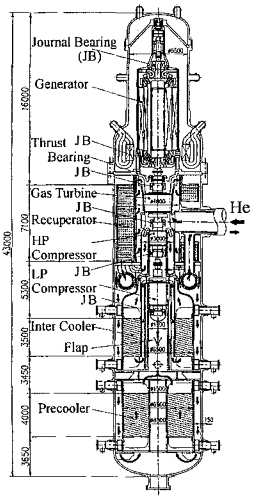


Fig. 11 Power Conversion Vessel Inner Structures

Main cooling system (gas turbine)

A heat balance of the primary circuit and PCV internals are shown in Fig.10 and Fig.11. The heat cycle is closed, recuperated and intercooled cycle, of which the plant efficiency reaches as high as 47%. The gas turbine power generation system is composed of a generator, a low pressure compressor, a high pressure compressor, a recuperator, a precooler and an intercooler. Those components are vertically arranged and contained in a PCV. Turbo-machines are coupled to a single-shaft. The height and the inner diameter of the PCV are 43m and 8m respectively. The PCV is supported at the cross duct level by floating support systems, which are adopted by conventional PWRs.

In this preliminary conceptual design study, each component is not designed in detail because at this phase I study stage, feasibility of core melt proof safety design and plant economics are the key points to be evaluated. Gas turbine power and some specifications are determined referencing the design study of Muto[2] and GT-MHR[3]. The vertical arrangement is determined mainly from space saving because horizontal arrangement makes the steel reactor containment vessel large.

Auxiliary core cooling system

An auxiliary core cooling system (ACCS) and an heat exchanger (HX) concept are shown in Fig.12 and Fig.13, respectively. The ACCS rejects heat from core under normal, such as reactor trip, shutdown, fuel exchange, etc., and accident conditions. In the case of loss-of-forced circulation events due to multiple failures of emergency diesel power generation systems, the core heat is removed by the natural circulation in the reactor through HXs then transferred to secondary loops and thrown away to the air.

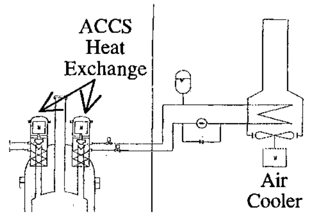


Fig. 12 Auxiliary Core Cooling System Concept

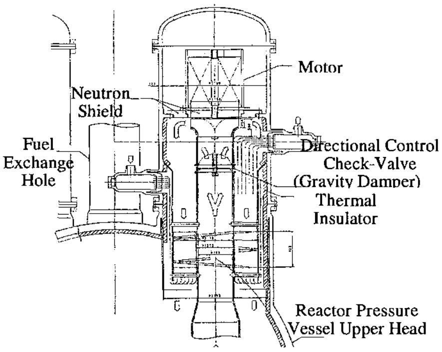


Fig. 13 Auxiliary Core Cooling System Heat Exchanger

When ACCS is operated, directional control check valves at the inlet of HXs open and coolant flows from reactor upper plenum into the HXs, down the path between the RPV and the inner containment vessel and flows into the core from the lower plenum. The inlet valves open automatically due to the pressure difference arose by a gas turbine generator trip between the inner and the outer side of the inner containment vessel.

The coolant of the secondary side of the ACCS is pressurized water. The pipes of ACCS HX secondary side penetrates the RPV, the containment and cooled by air cooling system. The coolant is circulated by pump power or natural circulation if necessary.

The entire ACCS comprises 4 systems and each system has 50% heat rejection capacity by forced circulation. Two ACCSs are supplied with power from a emergency diesel power generation system. Therefore when single failure is assumed, two ACCSs can be expected.

Safety analysis

The safety design goal is the accomplishment of the core melt proof characteristics.

The core melt and re-criticality should be avoided without any active component actuations even under severe depressurized accident conditions, namely, coolable geometries of the core should be kept and the core should be cooled only with passive components and natural circulations in the sequence (depressurized accident + without scram + without active component actuation). (Released FP from the core is allowed in CDA and it's retained in the containment.)

In a preliminary safety analysis it was studied first that how much of the core power density have to be decreased in order to satisfy the safety goal without the flow restrictors or the passive shutdown equipments. An allowable limit temperature of the core is determined to be 2200°C based on literatures as the maximum temperature that SiC/SiC fuel compartments can maintain the coolable geometry.

As the result of the preliminary analysis it was found that the core with larger core power density than 35MW/m^3 cannot meet the safety goal under the following scenarios.

- Depressurized accident (large pipe break, break area 100cm^2) + with scram + natural circulation
- Depressurized accident (small pipe break, break area 50cm^2) + without scram + natural circulation

And the core power density less than 30MW/m^3 is impossible because of the following reasons.

- Core nuclear performance become worse, the breeding ratio cannot reach 1 with the burnup 150GWd/t and much lower than 1.2 even with the burnup of 100GWd/t.

The diameter of the RPV exceeds the dimension that can be manufactured economically.

Taking into account the above issues and the installation of the additional safety equipments mentioned below, the core power density is fixed to 30MW/m^3.

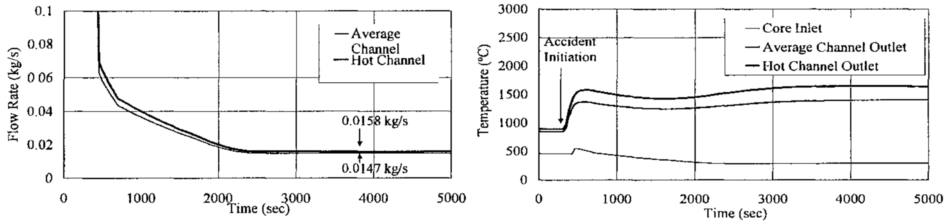
- Flow restrictor to limit the break area below 50cm^2.
- Passive shutdown equipment.

Safety analysis of the scenario (depressurized accident + scram failure + passive shutdown equipment actuation + natural circulation) was conducted based on the preliminary analysis.

Simple pressure nodes and flow paths junction model was applied considering the complexity of the safety transient analysis. The characteristic values of the core model such as pressure loss coefficients etc. are verified and modified by the detail analysis using general-purpose 3D finite volume method code STAR-CD. The core is modeled by two channels, an average and a peak channels in order to calculate core temperature distribution taking into account a flow distribution between the channels.

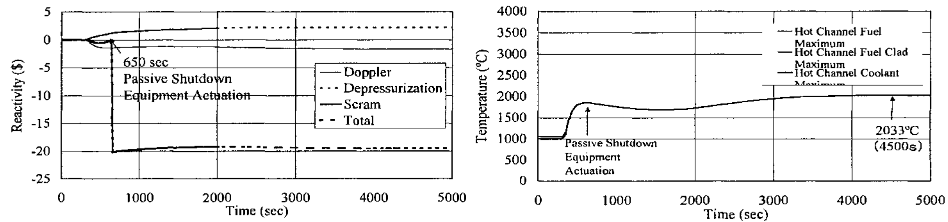
Reactivity, flow rate, temperature changes of the safety analysis result are shown in Fig.14. The fuel temperature rises after a depressurization event due to scram failures and the insertion of depressurization reactivity. After 350sec passive shutdown equipments are actuated and repress the temperature rise. The CPF and the fuel compartment reach the maximum temperature 2033°C after 4200sec. The maximum temperature 2033°C is below the allowed temperature 2200°C. Judging from the results, the actuation of the passive shutdown system can be delayed further about 300sec.

The safety analysis showed the preliminary plant design satisfied the safety goal and the core melt proof FBR design concept was realized.



Flow Rate

Core Temperature



Reactivity

Core Temperature

Fig. 14 Severe Accident Analysis Results
(Loss of Coolant+Without Scram+Natural Circulation)

HELIUM COOLED GAS TURBINE FBR (SEALED PIN FUEL)

The core melt proof safety of helium gas turbine FBR(CPF) is accomplished by small core power density (30MW/m^3), however that result in insufficient nuclear performance (the burnup 95GWd/t, the breeding ratio 1.09), which is mainly due to the small fuel to core volume ratio (about 9%: fuel volume / active core volume). In order to improve the ratio, another core design concept of CMPT was studied, of which fuel is sealed-pin type and uses Nb based high temperature resisting material for the clad. The study achieved excellent core performance, the fuel to core volume ratio about 30%, the core power density 100MW/m^3, the burnup 150GWd/t and the breeding ratio 1.17. However the actuation of the passive shutdown equipments is necessary at the time less than only a few ten seconds after the accident initiation. It was concluded it's impossible to design such passive shutdown equipments for the gas cooled reactor of which heat transfer ability is small.

CCT preliminary design concept using high temperature resisting and sealed pin fuel is being studied. In that case the core melt might occur on the severe accident conditions and the melt core would be cooled without re-criticality by the core catcher.

CONCLUDING REMARKS

The outline of the gas cooled FBR Phase I study conducted in Feasibility Studies on Commercialized FBR Systems was described. The preliminary design concept of the carbon dioxide cooled, steam turbine cycle and sealed pin fuel FBR was briefly explained and that of the helium cooled, gas turbine cycle and coated particle fuel FBR was described in detail.

The preliminary design concepts incorporate many innovative technologies requiring R&D. Therefore future R&Ds are essential. Especially the followings are the most important R&D items influencing on the feasibility of the design concept.

- Passive shutdown equipment
- CPF productivity, strength and irradiation characteristics
- Fuel assembly, strength and irradiation characteristics
- Gas turbine

- Thermal insulator and liner material
- ACCS and directional control check valve
- Natural circulation core cooling characteristics in the reactor

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