Status report 79 - A Passive Safty FBR Reactor – “KAMADO FBR” CRIEPI (Japan) (KAMADO FBR)

Overview

Full name	A Passive Safty FBR Reactor – “KAMADO FBR” CRIEPI (Japan)
Acronym	KAMADO FBR
Reactor type	Loop Type Reactor
Coolant	Carbon Dioxide
Moderator	No Moderator
Neutron spectrum	Fast Neutrons
Thermal capacity	3000.00 MWth
Electrical capacity	1000.00 MWe
Design status	Conceptual Design
Designers	CREIPI
Last update	04-04-2011

Description

Introduction

The concept of a passive-safety FBR reactor "KAMADO FBR" ("KAMADO" means a Japanese traditional kitchen range for cooking with firewood in Japanese) was proposed in 2008 by the Central Research Institute of Electric Power Industry (CRIEPI), Japan. KAMADO FBR is the modified concept of the passively safe thermal reactor “KAMADO” [1]. The KAMADO-FBR concept is based on a synthesis of the design approaches used in light water reactors (LWRs), CO_2 gas cooled reactors and pool type research reactors.

The design objective of the KAMADO-FBR is to develop a nuclear reactor with negligible possibility of a core meltdown accident, and to solve the problem of limited uranium resources. The KAMADO-FBR concept provides for a simple plant system design without a reactor pressure vessel, emergency core cooling system (ECCS), re-circulation systems (as in BWRs), etc. Therefore, construction cost is expected to be equal or sufficiently low, comparable with conventional large scale LWRs.
The R&D for this reactor concept has been fully performed and funded by the CRIEPI.

1.1 Applications

The KAMADO-FBR is designed to produce 1000 MW(e), assuming a generating efficiency of 33%. As the KAMADO-FBR concept uses no reactor pressure vessel, and is capable of employing different core sizes, the total output is flexible (MW to GW).

Since the KAMADO-FBR has a reactor water pool at atmospheric pressure and low temperature similar to pool type research reactors, the irradiation by neutrons and Gamma-rays around the reactor core is available for various uses. With the Gamma-ray heating around the reactor core, very high temperature (> 800ºC) steam can be produced; this very high temperature steam is then directed to the outside of the reactor water pool, Fig. 1, and could be transported well away from the reactor to be used for hydrogen production based on a thermochemical process. It is expected that several thousands of m^3/ hour of hydrogen could be produced using highly efficient hydrogen production technology and the equipment installed outside of the nuclear reactor with a 3000 MW(th) core.

1.2 Special features

The KAMADO-FBR is designed as a land based nuclear power station. However, its use within a floating power plant is not excluded.
The KAMADO-FBR has a simple plant system design without a reactor pressure vessel (RPV), ECCS, etc., which simplifies the construction and transportation of the components to a site.

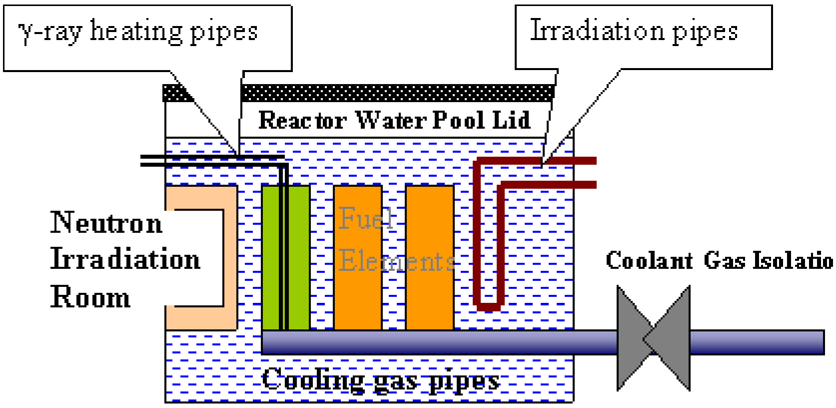

FIG. 1. Concept of KAMADO-FBR and possible use of neutron and g-ray irradiation

Attributes	Design particulars
Core configuration	Vertical, pressure tube type
Fuel	18% Pu_t MOX fuel (20% enriched UO_2 fuel option is available)
Cladding	Stainless steel
Moderator	No moderator
Coolant	super critical CO_2 (Inlet/outlet temperatures are about 200ºC / 400ºC)[1]
Number of fuel rods	36 fuel rods per a fuel element
Inner diameter of a fuel rod	10 mm

Attributes	Design particulars
Fuel element structure material	Stainless steel
Active fuel length	3.7 m
Fuel element lattice pitch	125 mm
Number of fuel elements	1073
Average linear heat rate	20 kW/m
Average core power density	48 MW/m^3
Core size	core diameter: 5.6 m (core:4.6m + Blanket)
Coolant pressure	About 15MPa
Mode of core heat removal	Forced circulation
Primary shutdown system	Mechanical shut-off rods
Secondary shutdown system	Liquid poison injection in the reactor pool

Table 1. Summarized Technical Data

Description of the nuclear systems

2.1 Installed capacity

The KAMADO-FBR is designed to produce 3000 MW(th), generating 1000 MW(e).

2.2 Mode of operation

The KAMADO-FBR can be operated in base load, as well as load-follow modes.

2.3 Load factor / Availability

The KAMADO-FBR targets 90% load factor and availability, like conventional LWRs.

Some tentative design characteristics of the KAMADO-FBR are given in Table 1.

2.4 Simplified schematic diagram

The fuel element is composed of MOX (Mixed Oxides Fuel) fuel rods and cooling inert gas areas (Fig. 2). The fuel rods are arranged internally in the fuel element box and connected tightly with the fuel element box. Thermal powers of fuel rods are mainly removed with inert gas, and a few percent of the thermal power changes water into steam around the fuel element. CO_2 flows upward and cools fuel rods and flows downward in the central portion of the fuel element, that is, reverse-U character type flow.

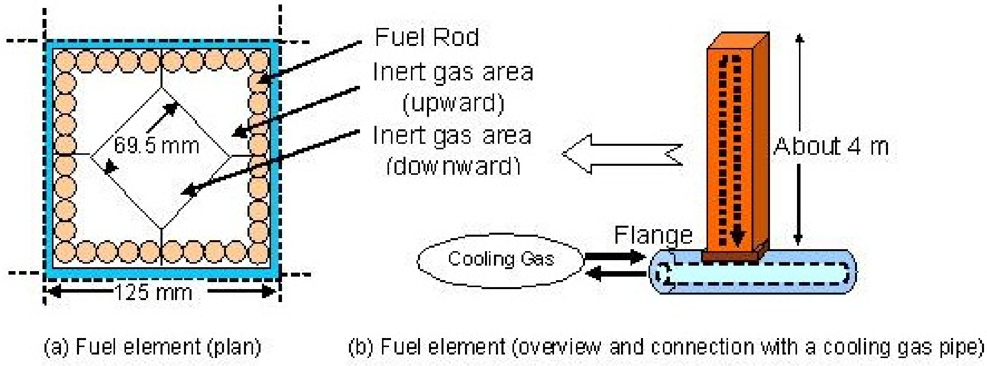

FIG. 2. Conceptual design of the fuel element.

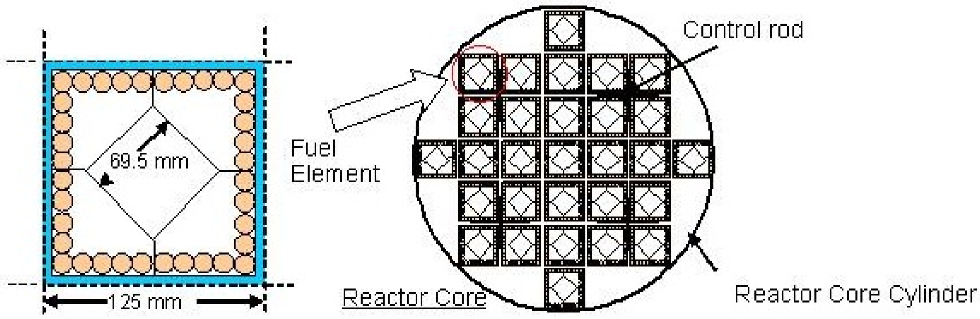

FIG. 3. Conceptual design of the reactor core.

The fuel elements are arranged in a nuclear reactor cylinder, which works as a mechanical structure without a lid. There is no pressure difference between inside and outside of the nuclear reactor cylinder (Fig. 3). Control rods of the cluster type are inserted between the fuel elements.

Figure 4 illustrates the basic concept of the present KAMADO-FBR design. In normal power operation, the fuel rods are cooled with inert gas flow. The heat of the coolant gas is transferred to the steam turbine via the steam generator. In case of loss of coolant/flow accidents, decay heat of the fuel rod is removed by way of the surface of the fuel element box to the reactor water pool (atmospheric pressure and low temperature, the final heat sink) directory (Fig. 5).

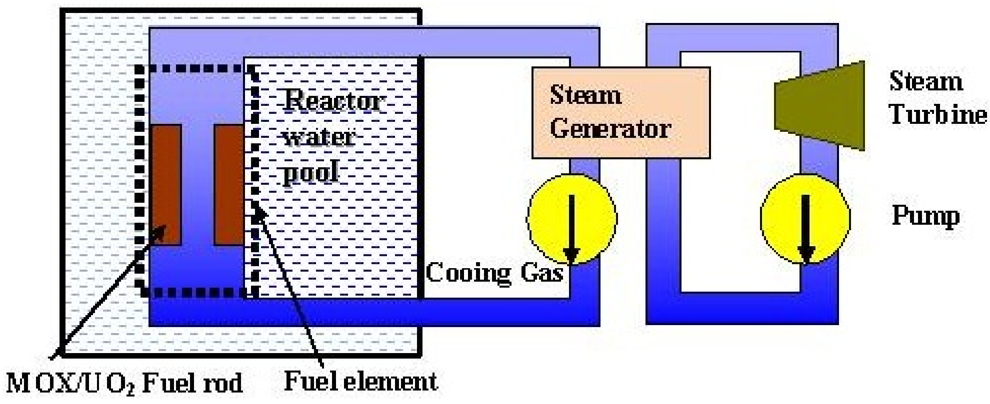

FIG. 4. Basic concept of KAMADO-FBR.

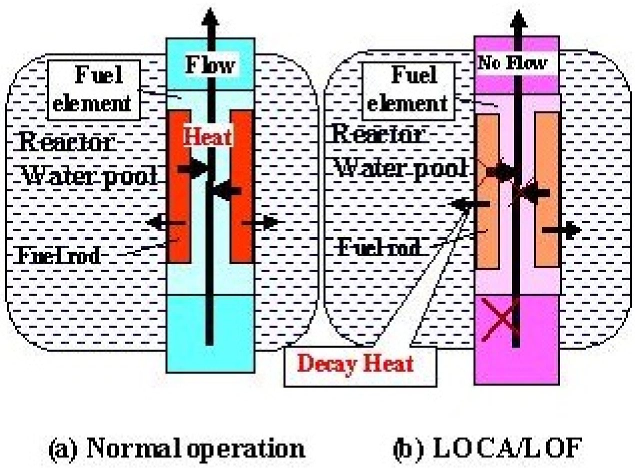

FIG. 5. Heat removal paths in normal operation and in LOCA/LOF.

2.5 Neutron-physics characteristics

The KAMADO-FBR has an FBR-type neutron energy spectrum. In normal power operation, water around fuel elements is heated and changed to steam, that contributes to harder neutron energy spectrum. Water around fuel elements is re-flooded after the reactor shutdown.

The KAMADO-FBR core has a breading ratio of 1.1 and reaches high burn-ups (more than 100 MWday/kg HM) with 18% Pu_t MOX fuel.

The re-flooded water causes a softer neutron energy spectrum (thermal energy neutron increment). A positive reactivity insertion with the thermal neutron energy spectrum is prevented by adding thermal energy neutron poison of gadolinium (about 1%) to the fuel pellets. The reactivity effects of the re-flooded water have a negative value due to this neutron poison.

The calculations performed with continuous energy Monte Carlo code MVP-II show that re-flooded water has negative reactivity effect of –9 % Delta k/k (at BOL) and temperature coefficient of -7.7E-5 % Delta k/k/ºC. These coefficients are considered sufficient to secure passive shutdown of the reactor core in accidents.

2.6 Activity control mechanism

In the KAMADO-FBR there are two independent and diverse systems of reactivity control. The mechanical control rods are used to compensate reactivity changes due to fuel burn-up and operational reactivity changes; the primary reactor shutdown is assumed to be passive. A liquid poison injection system in the reactor pool is available as a secondary shutdown system.

2.7 Cycle type and thermodynamic efficiency

Primary coolant of The KAMADO-FBR is CO_2 gas (about 15MPa, super critical phase). Through the steam generator, reactor generated heat is transferred to steam turbine. The thermodynamic efficiency (target) is expected to be 33%.

2.8 Thermal-hydraulic characteristics

Due to primary coolant of CO_2 gas, the limitations of thermal-hydraulic characteristics of the KAMADO-FBR are maximum temperatures of fuel rods and structure materials. Creep behaviour of fuel rod cladding and structure materials (stainless steel) should be also evaluated.

2.9 Maximum/average discharge burn-up

The KAMADO-FBR fuel elements have a possibility to reach high burn-ups (more than 100 MWday/kg HM, or about 11% FIMA) with 18% Pu_t MOX fuel. 20% enriched UO_2 fuel also can be used as uranium start up.

2.10 Fuel lifetime/period between refuellings

The KAMADO-FBR refuelling concept is similar to that of conventional LWRs. Since the KAMADO concept has a simple plant system design, plant maintenance becomes easy too. Therefore shorter refuelling/outage time is expected. Assuming 360 effective full power days (EFPD) of operation and 40 days of refuelling, the target load factor of 90% could be achieved.

2.11 Mass balances/flows of fuel materials

The inventory of heavy metals is about 100 t for the core region and 100 t for the blanket region in a 1000 MW(e) KAMADO-FBR plant. In case of a 10batch refuelling, about 10 t HM of MOX fuel and 10 t U of depleted uranium are loaded / unloaded annually. Through a reprocessing plant, Pu and depleted uranium are recycled. Therefore 2t depleted uranium is necessary for present KAMDO-FBR system annually (Fig. 6).

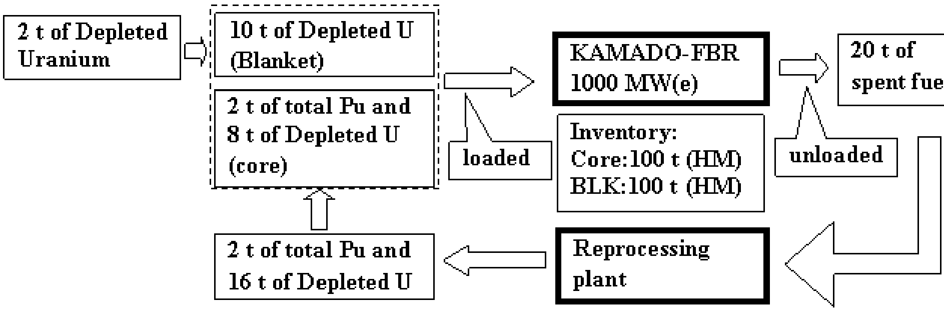

FIG. 6. Annual mass balance of uranium (fuel burn-up ~ 100 M·day/kgHM).

2.12 Economics

The cost reduction target for the KAMADO-FBR is equal or less than conventional large scale LWRs. Simplicity of the plant system such as primary cooling system, engineered (active) safety systems and other reactor systems are expected to contribute to cost reduction.

On the other hand, there are possibility of enlargement on steam generator and the reactor building due to heat transmission performance of carbon dioxide. Therefore research and development of gas turbine and the steam generator is necessary using the characteristic of the supercritical phase carbon dioxide (Table. 2).

2.13 Outline of fuel cycle options

The KAMADO-FBR fuel cycle concept could be similar to that of FBRs. Spent fuel from the KAMADO-FBR could be reprocessed in a reprocessing plant. Pu and U would be recycled and used as new MOX fuels for the KAMADO-FBR.

Because the size of a fuel element is similar to that of conventional LWRs, LWR spent fuel pools are available for storage of KAMADO-FBR spent fuels. However the number of KAMADO-FBR spent fuel elements loaded in a transport cask should be reduced due to higher decay heat and radiation than LWR spent fuel.

3.1 Safety concept and design philosophy

The design objective of the KAMADO-FBR is to develop a reactor with negligible probability of a core meltdown accident. To achieve this goal the KAMADO-FBR design strongly relies on the inherent safety features related to optimal core neutronics and the confinement of radioactive materials, and also makes use of passive systems for decay heat removal. An important feature of this design is passive decay heat removal achieved for the fuel elements installed in the reactor water pool operating at atmospheric pressure (1 atmosphere) and low temperature (< 60°C).

3.2 Provisions for simplicity and robustness of the design

The KAMADO-FBR has a simple plant system design without engineered safety systems. The KAMADO-FBR design ensures a high margin to fuel failure in accidents.

3.2.1 Passive systems safety features

The passive safety features are:

- Negative and negligible reactivity coefficients for LOCA/LOF and various events (providing a passive shutdown capability);
- Direct decay heat transfer to the reactor water pool (final heat sink);
- Low (atmospheric) pressure and temperature of the water pool.

The design features of the KAMADO-FBR provide a passive decay heat removal capability with all components of the reactor core and water pool acting as a passive decay heat removal system. In this, the residual heat removal (RHR) system is reduced to a water pool cooling system, which could be made non-safety-grade and passive.

The KAMADO-FBR has negative and negligible reactivity coefficients for LOCA/LOF and various events. In case of a loss of coolant or flow, the reactor will be shut down passively. Increases in the fuel element temperatures will be suppressed during several seconds after LOCA/LOF initiation by heat transfer to the reactor water pool (*Fig. 5*). Decay heat will be transferred passively to the reactor pool and, therefore, high temperature of the fuel elements can be avoided in LOCA/LOF.

The reactor water pool has enough heat capacity to absorb decay heat for 3 days without relying on operator actions. In case of a malfunction of the cooling system of the reactor pool, its temperature would increase slowly and operators will have enough time to shut down the reactor manually.

3.2.2 The active safety system features

The active safety systems are:

- A liquid boron injection system of the reactor pool, which is a reserve shutdown system;
- Coolant Gas Isolation Valve;
- Hydrogen combustion system.

The reactor pool lid and the Coolant Gas Isolation Valve, additionally enhance the reactor capability to confine radioactive materials, Fig. 1.

Hydrogen generated in the reactor pool (mainly due to the radiolysis caused by gamma-rays) could be treated by a combustion system similar to that used in conventional LWRs.

Since water of the reactor pool is important for the KAMADO-FBR safety concept, loss of water from the reactor pool should be prevented through appropriate design measures, such as double walls of the reactor pool, a monitoring system of water leakage, etc. Location of the reactor pool below ground level could inherently prevent accidents with the loss of pool water.

3.2.3 Structure of the defence-in-depth

The KAMADO-FBR has adopted the defence-in-depth concept with multiple barriers, such as fuel pellets, cladding, fuel elements, a shielded reactor pool and a shielded reactor building.

3.2.4 Design basis accidents and beyond design basis accidents

A tentative list of the design basis accidents includes:

- Loss of coolant accident (LOCA);
- Loss of flow accident (LOF);
- Malfunction of Coolant Gas Isolation Valve;
- Blockage of pipes or tubes;
- Reactivity induced accidents;
- Malfunction of the cooling system of the reactor pool.

In case of a loss of coolant/flow, the reactor will be shut down passively by the negative reactivity coefficients. Additionally, reactivity induced accidents can be controlled by such design features as gravity driven safety rods. In case of a malfunction of Coolant Gas Isolation Valve or a blockage of pipes or tubes (which cause negligible reactivity effects), the increase of the fuel element temperature leads to a negative reactivity insertion. The subsequent transient progressions are expected to be similar to the loss of flow accident, providing that detailed examinations should be performed.

The temperature distribution analysis of the fuel element design were executed with a two dimensional FEM code. The calculated temperature distribution during normal operation shows 893℃ for the maximum fuel pellet temperature, which is a similar value to the LWR fuel pellet temperature (*Fig. 7(a)*). Due to a value of 610℃ for the maximum fuel cladding temperature, it is necessary to use appropriate stainless steels for cladding materials in the present fuel element design.

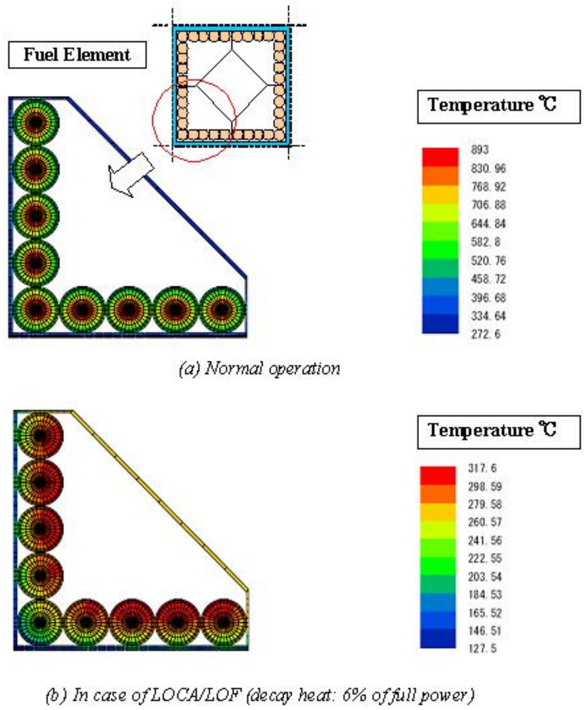

FIG.7. Temperature distributions in fuel element for (a) normal operation, or (b) for LOCA/ LOF condition.

The beyond design basis accidents may include:

- Anticipated transient without scram (ATWS);
- Total NPP blackout.

In an ATWS, e.g. even if the reactor does not stop its operation after LOCA/LOF, the temperature of the fuel elements will be passively suppressed and kept under the melting points of the fuel. Since the KAMADO-FBR has passive shutdown and decay heat removal capabilities, core meltdown is not expected in case of a total NPP blackout (loss of internal and external power supply).

Though the detailed safety and accident analyses have not been performed yet, the preliminary evaluations indicate that the KAMADO-FBR might be designed to essentially exclude a core meltdown accident.

3.3 Measures planned in response to severe accidents

The reactor water pool has enough heat capacity to absorb decay heat for more than 3 days without operator intervention. If necessary, external water can be injected into the reactor water pool from outside of the reactor building.

Since the KAMADO-FBR is designed to have a negligible possibility of core meltdown, a potential radiation exposure in accidents could be essentially reduced or eliminated.

A fuel pellet power density of 2.5×10^8 W/m^3, which is a typical value for LWR fuel pellets, is used for the present calculations. The heat transfer coefficient of steam outside of the fuel element was set to 1000 W/m^2/K, which is a conservative value for the heat transfer coefficient of very high quality (spray flow) boiling water.

In case of a LOCA/LOF, decay heat can be removed from the surface of the fuel element box to the reactor water pool, which is the final heat sink. *Fig. 7 (b)* shows the temperature distribution of the fuel element with decay heat of 6% of full power (at a few seconds after reactor shut down). In the present calculation it is assumed that there is no heat transfer to the carbon dioxide coolant. The calculated result shows the maximum temperature of 318°C, which can be allowed in design. Therefore fuel integrity can be achieved for LOCA/LOF and various events.

Description of turbine-generator systems

The turbine-generator concept of the KAMADO-FBR is similar to that of conventional LWRs. As the heat of the coolant gas is transferred to the steam turbine via the steam generator, the steam generator should be newly designed.

Electrical and I&C systems

Because the KAMADO-FBR core is located at the reactor water pool of atmospheric pressure and low temperature, the design of the Electrical and I&C systems should be easier than that of conventional LWRs.

Spent fuel and waste management

In the KAMADO-FBR, only fuel elements, control rods and reactor core support structures are irradiated (no pressure vessel, no radiation shielding concrete, etc.), which contributes to reduce the volume of wastes.

Plant performance

The KAMADO-FBR has a simple plant system design eliminating many components present in conventional LWRs. The targets for cost reduction in certain components of the KAMADO-FBR are given in *Table 2*.

Since the reactor basic shutdown and decay heat removal are passive, there is no need in dedicated engineered safety systems.

On the total, construction cost is expected by the developer to be equal or low compared with conventional large scale LWRs.

SYSTEMS	*COST REDUCTION TARGET AND APPROACHES*

PRIMARY COOLING SYSTEM	*25% BY ELIMINATING REACTOR PRESSURE VESSEL, STEAM RECIRCULATION SYSTEMS, SEPARATORS, ETC.*
ENGINEERED (ACTIVE) SAFETY SYSTEMS	*100% BY ELIMINATING ECCS AND ALL OTHER ENGINEERED SYSTEMS*
OTHER REACTOR SYSTEMS	*60% BY REDUCING THE RADIOACTIVE WASTE TREATMENT SYSTEMS, ETC.*
STEAM GENERATOR	*POSSIBILITY OF ENLARGEMENT. R&D OF COMPACTION IS NECESSARY.*
TURBINE SYSTEM	*NOT CHANGED*
I&C SYSTEM	*NOT CHANGED*
BUILDINGS	*POSSIBILITY OF ENLARGEMENT DUE TO STEAM GENERATOR*
OTHERS	*NOT CHANGED*

TABLE 2. Targets for cost reduction

Since the control rod drive (CRD) mechanisms can be located above the reactor pool (no radiation, room temperature area), easy maintenance of the CRDs is achievable.

Development status of technologies relevant to the NPP

As the KAMADO-FBR core is small and the pressure vessel is unnecessary, reactor core of 3 GW(th) (5.6 m diameter) can be designed in the containment (BWR) or in a reactor cavity (PWR) of the existing middle scale light-water nuclear reactors. The KAMADO-FBR core can be set up by removing the reactor pressure vessel, and assuming containment (BWR) or reactor cavity (PWR) to be used as the reactor water pool in concept of the present FBR core (FIG.8).

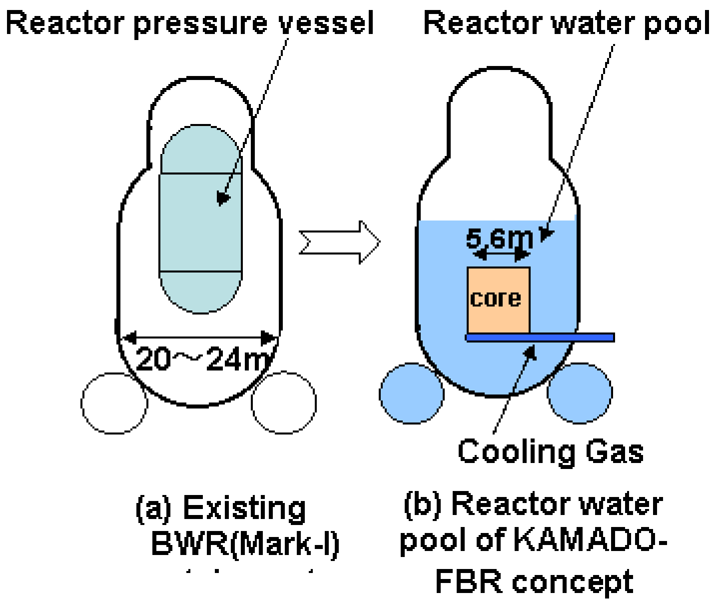

FIG. 8. Concept of replacing an existing LWR to the KAMADO-FBR

Deployment status and planned schedule

The preliminary conceptual design of the KAMADO-FBR is in progress. All activities on design and technology development for the KAMADO-FBR are performed and funded by the CRIEPI of Japan. No other similar concepts are under design elsewhere.

The KAMADO-FBR concept is similar to conventional LWRs with respect to fuel rods, control rods, steam turbine and others. However, a fuel element, primary gas coolant system and steam generators are the main innovative components to be developed and demonstrated. The fuel elements and the reactor pool technology could, perhaps, be developed and demonstrated using an experimental base provided by pool type research reactors and high flux reactors. Primary gas coolant system and steam generator could be validated using thermal-hydraulic facilities with mock-up heating. The list of enabling technologies for the KAMADO-FBR is given in *Table 3*.

It is foreseen that the KAMADO-FBR concept could be developed and demonstrated using the pool type research reactors, high flux reactors and cold (non-radioactive) experimental facilities.

As listed in *Table 3*, the innovative fuel elements and the primary cooling system with a new technology would require a substantial amount of RD&D.

Technology	Status of development
Fuel rods	Available, similar to LWR fuel rods
Fuel elements	Research design and demonstration (RD&D) necessary
Control Rods / CRD	Available, similar to BWR control rods An option to locate CRD mechanisms above the

	reactor water pool should be examined.
Primary cooling system	RD&D necessary to prove reliability of super critical CO_2 coolant cooling system.
Steam Generator	RD&D necessary to prove reliability
Radioactive waste treatment system	RD&D necessary to prove reliability
Reactor water pool	RD&D necessary. Some experience of pool type research reactors and high flux reactors could be of relevance.
Residual heat removal (RHR) system	Available, RHR is reduced to water pool cooling system, which is not a safety grade system and could be designed using available technologies
Hydrogen production system using process steam*	RD&D necessary
Turbine system	Available, standard equipment can be used
Electrical system	Available, standard equipment can be used
Building	Research design and demonstration (RD&D) necessary

* Hydrogen production system is optional. The equipment using a highly efficient hydrogen production technology is to be installed away from the nuclear reactor.

Table 3. List of enabling technologies for KAMADO-FBR

References

1. IAEA-TECDOC-1485, "Status of innovative small and medium sized reactor designs 2005 -Reactors with conventional refueling schemes" (2006).
2. MATSUMURA, T., et al., Core Concept of a Passive-Safety Fast Reactor "METAL-KAMADO" and Reactivity Coefficients, Progress in Nuclear Energy 50, pp 225-229 (2008).
3. MATSUMURA, T., et al., A New Passive Safety FBR Concept of "KAMADO" – Easy Replacement from the Existing Light Water Reactor to FBR", ICAPP 9370, Tokyo, Japan (2009)

Technical data

General Information - FR

Reactor Name	A Passive Safty FBR Reactor – "KAMADO FBR" CRIEPI (Japan)
Reactor Thermal Output	3000 MWth
Power Plant Output, gross	1000 MWe
Primary Circuit Coolant	Carbon Dioxide
Power Coversion System	
Primary Circuit Configuration	Loop
Type of Cycle	Indirect
Thermodynamic Cycle	Rankine