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Development of Multi-purpose Microreactor
- Challenge to All-solid-state Core -

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Microreactor is an innovative nuclear reactor that provides new value distinct from conventional land-based power generation reactors. Key features include compact size, portability, and inherent safety, enabling its use in regions with underdeveloped power grids. Mitsubishi Heavy Industries, Ltd. is developing a multi-purpose modular microreactor that addresses diverse needs. This study examines the safety and core concepts of all-solid-state core featured in this microreactor. Thermal transport simulations confirmed that adopting highly oriented graphite, a high-thermal-conductivity material, as the core material ensures adequate heat transfer from the core to the power generation system under normal operating conditions.

1. Introduction

Microreactors are significantly smaller than the existing power generation reactors on land. Their development is in progress among various organizations with the aim of using them as a power/heat source in the regions with underdeveloped power grids. In the early stages of the nuclear power field, research reactors were utilized by universities and research centers, and small reactors were operated in remote areas. In later years, however, the economic competitiveness with other energy sources was demanded, and the civilian application was oriented toward large power plants. While this trend is expected to continue for some time, the application will not remain limited to large-scale power generation, but will be adapted for changing needs when considering the megatrends such as the coming population decline and rural depopulation. It will therefore become necessary for nuclear energy to be usable under various conditions, serve as a safe, stable small power/heat source, and be adapted for new applications such as energy storage and multi-purpose applications, as shown in **Figure 1**. The needs of the areas such as depopulated areas, remote islands, mountainous areas, heavy snowfall areas and disaster-stricken areas are especially required to be fulfilled. There are also overseas cases in which microreactors are installed as a university's facility for the educational and research purposes. Looking to the future, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is developing an innovative multi-purpose modular microreactor that addresses diverse needs(1).

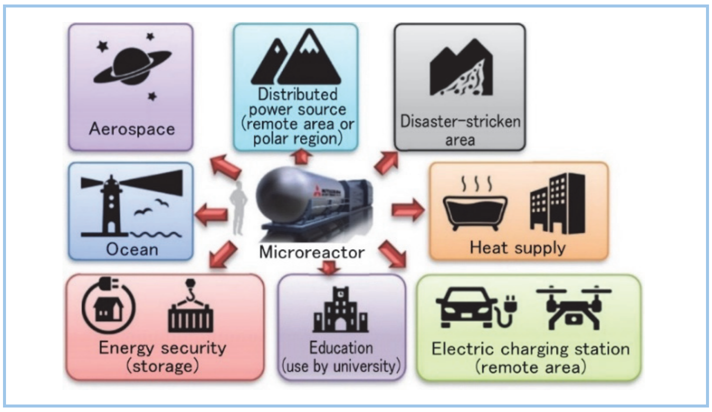

Figure 1 Conceptual diagram of microreactor applications

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2. Characteristics of all-solid-state core

2.1 Major specifications

In conventional nuclear power reactors, reactor coolant loss caused by an accident poses the highest risk of radioactive material external leakage. In order to eliminate the fundamental cause, MHI's multi-purpose modular microreactor does not use fluid coolant for core. Instead, it adopts the concept of all-solid-state core in which a high thermal conductor is used to transfer heat from the core to the power generation system. In the conventional reactors, as the coolant fluid flows directly through the core for cooling, many of the safety systems are intended to handle the reactor coolant-induced accidents/events. However, as MHI's all-solid-state core involves no such direct flow through the core, the number of possible accident scenarios is lower than that of the conventional reactors(2). Even if the core temperature rises, nuclear fission reaction will naturally decrease and the thermal output will be stabilized at a constant level. The design of microreactor achieves such inherent safety. As shown in **Table 1**, a single module of microreactor typically has a thermal output of 1 MWt, equivalent to approximately 300kWe of electricity output. This output level is suitable for power/heat supply to a small community in regions with underdeveloped power grid. As multiple modules can be connected together, the power output can be ramped up as needed. After manufactured in a factory, portable microreactors are transported to the site and can start the operation with minimum on-site work. Such portability is realized by designing the microreactor to have a very small core of a maximum of 1 m in diameter and 2 m in length. High-assay low-enriched uranium (HALEU) fuel with uranium enriched up to 20 wt% is adopted to ensure stable operation up to 10 years without refueling. The operation control system, which constantly collects data on the plant's reactor and power generation system, is planned to be equipped with a digital twin, so that the reactor conditions can be monitored using simulation. With this technology, it becomes possible to operate or remotely monitor by a small number of staff. Moreover, even if a reactor accident occurs, the reactor will automatically shut down and the high thermal conductor with superior heat removal performance will cool the decay heat in the core only by natural air cooling. For the power generation system, the adoption of compact and highly efficient supercritical CO_2 cycle is under consideration.

Table 1 Major specifications

Item	Specification
Reactor type	High thermal conductor-cooled reactor (all-solid-state core)
Heat / power output	≥1 MWt / ≥300 kWe
Core size	≤1 m in diameter, ≤2 m in length
Cooling mechanism	Core system: thermal conduction using the high thermal conductor Power generation system: CO_2 gas cooling
Fuel	HALEU fuel
Continuous fuel lifetime	≥10 years (with full output)
Operation control	Operation and remote monitoring by a small number of staff
Safety system	Passive reactor shutdown system and natural cooling system

2.2 Core concept

As shown in **Figure 2**, the core is located in the center of the reactor vessel, and therein lies the emergency reactor shutdown system. Placed inside the core are fuel and a high-thermal-conductivity material. The latter is highly oriented graphite material with the property of anisotropic thermal conduction, and the orientations of individual crystals are in the same direction. Installed around the core are the control drums and graphite reflectors, both of which are used during normal operation. The control drums are partially coated with neutron absorbing material. By adjusting the angle of the drum, the reactivity in the core is controlled. The heat generated from fuel is radially transported by thermal conduction through highly oriented graphite, and then heats CO_2 gas in the heat transfer tubes, which are embedded in highly oriented graphite and is a component of the power generation system. The CO_2 gas flows to the reactor is distributed among the heat transfer tubes through the ring manifold. The CO_2 gas heated in the core is re-collected at the manifold to flow to the power generation system. A bellows structure is adopted to absorb thermal deformations of the reactor vessel, heat transfer tubes and manifolds.

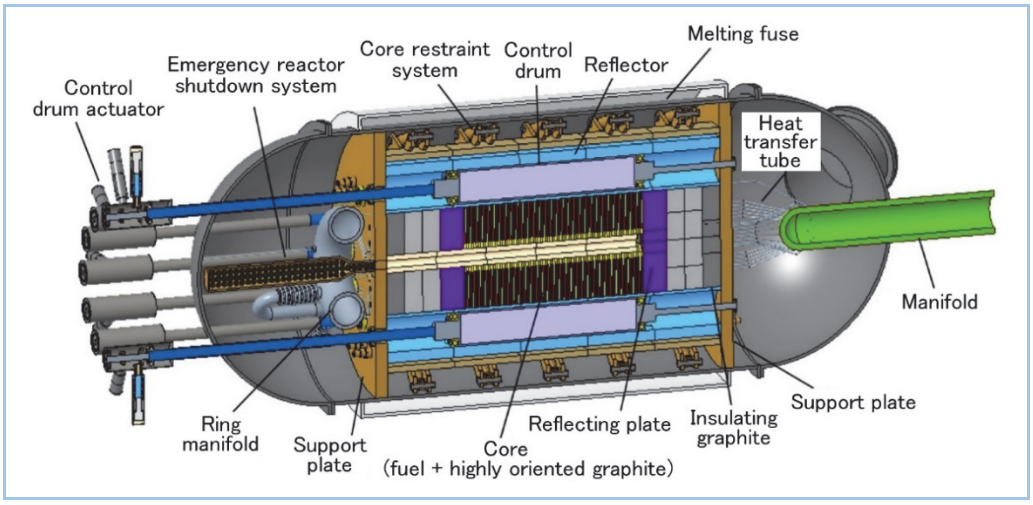

Figure 2 Reactor structure design plan

2.3 Safety concept

In general, reactor design incorporates three key safety elements: “shutdown,” “cooling” and “confinement”. MHI’s microreactor is also designed to ensure that these elements function properly. The first “shutdown” pertains to the emergency reactor shutdown by rotating the control drum. Even if the control drum fails to function, the emergency reactor shutdown system passively inserts the neutron absorbing material into the reactor, automatically shutdown the reactor. The next function of “cooling” is based on the removal of heat by the power generation system. Even if the power generation system fails to function, the decay heat from the core is designed to be removed by natural air convection or cooling by radiation (natural cooling mode). As shown in **Figure 3**, below the outer wall of the reactor vessel is a vacuum layer, which serves as insulation. When the core temperature increases, the melting fuse will melt to open a relief vent letting air into the vacuum layer, thereby switching to the natural cooling mode. The simulation analysis has confirmed that decay heat can be effectively removed through natural cooling, without a significant temperature increase at the center of core(3). Lastly, with regard to the “confinement” function, radioactive materials are designed to be kept within the confines of the fuel area, reactor vessel, etc. As microreactors are small and portable, it has been advocated that their design be determined after fully considering the security against incidents including nuclear terrorism(4). Therefore, the defense-in-depth concept for nuclear security is adopted with the aim of designing a microreactor structure highly resistant to destruction(5).

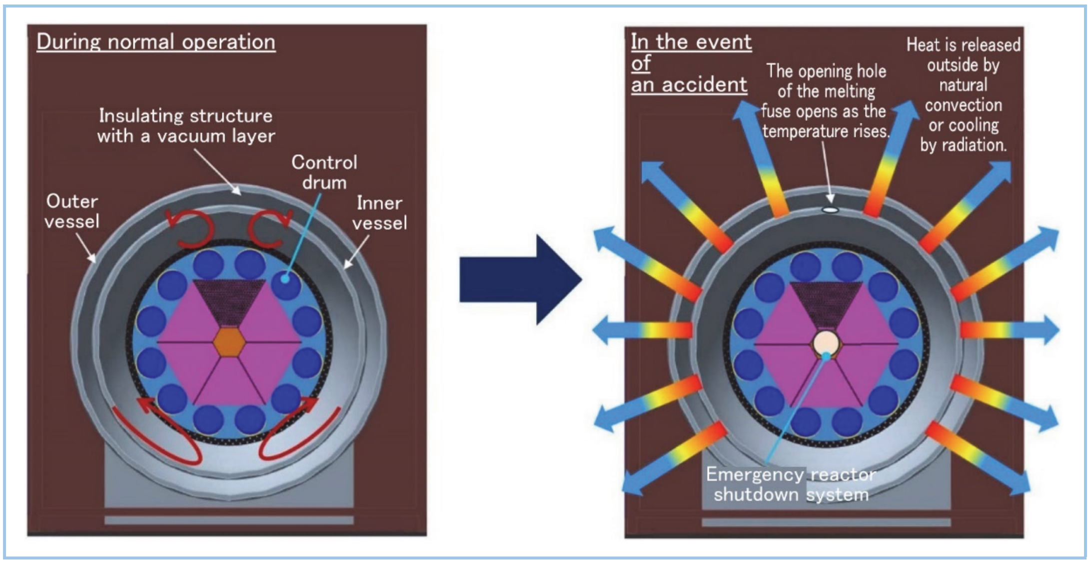

Figure 3 Concept of natural cooling mode

3. Feasibility of the all-solid-state core concept

3.1 Heat transfer performance of core material

In order to make all-solid-state core feasible, the core material to be used should have high thermal conductivity. Therefore, MHI is investigating the use of graphite-based material that combine lightweight properties with high thermal conductivity that is advantageous for portability. Specifically, highly oriented graphite, as shown in **Figure 4**, is under consideration for use as the core material. Previous studies have evaluated the engineering properties of highly oriented graphite (such as thermal conductivity, strength and workability) to assess its feasibility for all-solid-state core. As shown in **Figure 5**, the thermal conductivity measurement results of highly oriented graphite indicate that its level is about six times higher than the graphite-based material conventionally in use in the field of nuclear power. The strength test and machining trials have also provided the basic data to confirm the material's suitability for use in reactor core material.

Figure 4 A sample of highly oriented graphite

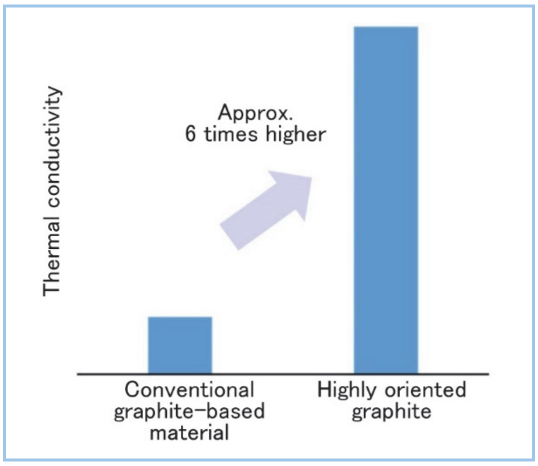

Figure 5 Thermal conductivity performance of highly oriented graphite

3.2 Heat transport assessment of all-solid-state core

As the assessment of heat transport performance of the core, simulation was performed to analyze the temperature distribution in the core, based on the measurement results of thermal conductivity obtained in Section 3.1 and taking into account the irradiation environment. In this evaluation, a three-dimensional thermal conductivity analysis code developed by MHI, based on MOOSE(6), a multiphysics simulation environment for nuclear reactors, is utilized to assess anisotropic thermal conductivity. **Figure 6** shows the results of temperature distribution in the core during normal operation. The heat generated by fuel in the core is properly transported by thermal conduction through highly oriented graphite to the heat transfer tubes of power generation system. The maximum temperature in the core is below 1600°C, which is the temperature threshold considered to cause the failure of graphite. This result confirms the core's structural integrity and effective heat dissipation through highly oriented graphite(7) during normal operations. The nuclear characteristics of the core and the structural integrity were assessed by simulation analysis. The results show that the core can be operated up to 10 years without refueling. Additionally, the core can reliably achieve shutdown conditions using the control drums or a passive emergency shutdown system(8). Thus, the technological feasibility of the microreactor has been obtained in terms of the criticality, shutdown margins, fuel lifetime, structural integrity, etc. These results confirm the feasibility of the basic design concept for the all-solid-state core. While advancing the conceptual design of the microreactor, we will carry out essential elemental tests to validate its safety.

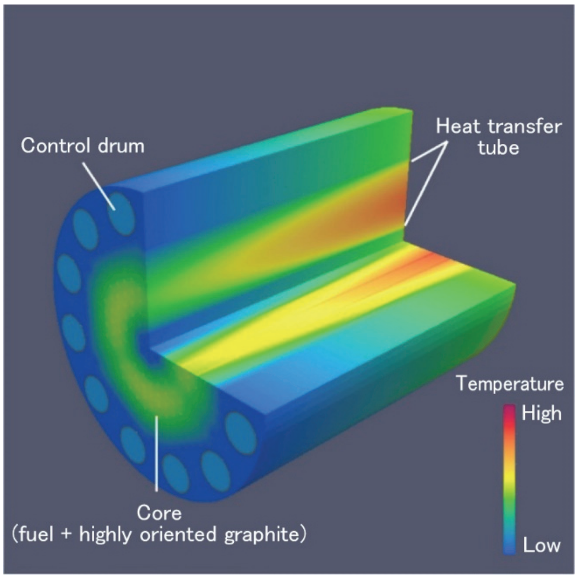

Figure 6 Simulation results of temperature distribution in the core

4. Conclusion

MHI's multi-purpose modular microreactor under development adopts the all-solid-state core concept to prioritize safety. To evaluate the feasibility of the reactor concept, the core and safety designs were established. The basic data on candidate core materials, such as highly oriented graphite, were obtained, and various simulation evaluations confirmed the feasibility of the heat dissipation performance - a key technology of the all-solid-state core concept.

MHI will continue to advance the development of this microreactor in collaboration with potential users, working toward its practical implementation.

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