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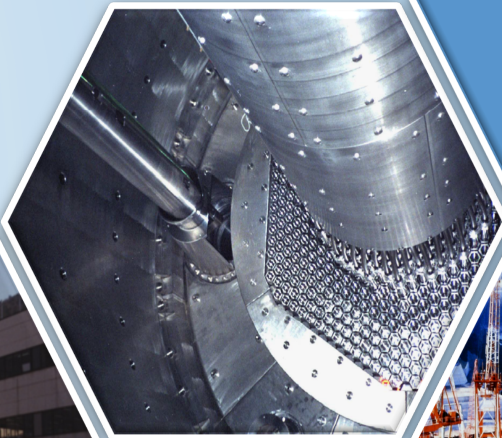
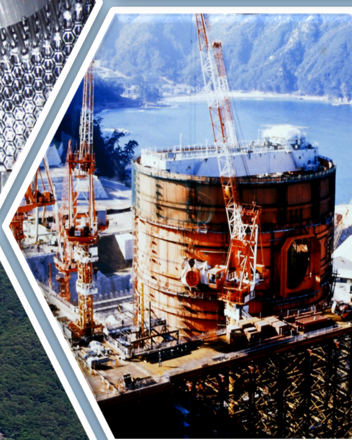
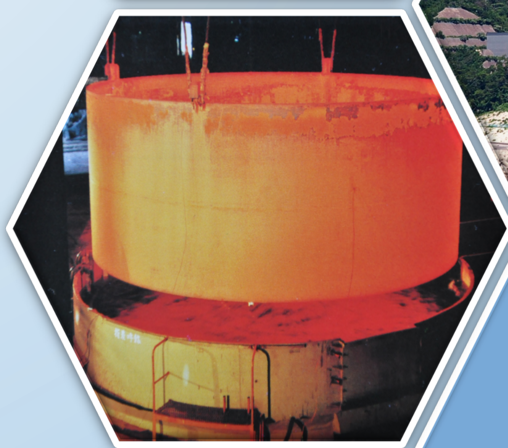
Prototype Fast Breeder Reactor MONJU

－Its History and Achievements－

(Translated Document)




Tsuruga Comprehensive Research and Development Center
Sector of Fast Reactor and Advanced Reactor Research and Development
Japan Atomic Energy Agency

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Tsuruga Comprehensive Research and Development Center
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The prototype fast breeder reactor Monju has produced valuable technological achievements through design, construction, operation and maintenance over half a century since 1968. This report compiles the reactor technologies developed for Monju, including the areas: history and major achievements, design and construction, commissioning, safety, reactor physics, fuel, systems and components, sodium technology, materials and structures, operation and maintenance, and accidents and failures.

Keywords: Monju, Prototype Fast Breeder Reactor, SFR, Advanced Technology Development, Design and Construction, Operating Experience, History

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This report is translation of JAEA-Technology 2019-007.
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高速増殖原型炉もんじゅ
－その軌跡と技術成果－

（翻訳資料）

日本原子力研究開発機構
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敦賀総合研究開発センター

（2019 年 12 月 12 日受理）

高速増殖原型炉もんじゅは、1968 年の研究開発着手から半世紀にわたる設計、建設、運転、保守等を通じて、数多くの貴重な成果を生んできた。本報告書は、「開発経緯と実績」、「設計・建設」、「試運転」、「原子炉安全」、「炉心技術」、「燃料・材料」、「原子炉設備」、「ナトリウム技術」、「構造・材料」、「運転・保守」、「事故・トラブル経験」の技術分野について、特徴や技術成果を取りまとめたものである。

本報告書は JAEA-Technology 2019-007 を英訳したものである。
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Message from the President

The Prototype Fast Breeder Reactor Monju was transferred to the decommissioning phase as a consequence of government policy set out in December 2016.

The development of the fast breeder reactor (FBR) based on domestic technologies was determined by the Japanese government from the perspective of stable energy supply and the effective use of uranium resources in a country with poor energy resources. As a central operating organization, the Power Reactor and Nuclear Fuel Development Corporation, currently the Japan Atomic Energy Agency (JAEA), was founded in 1967, and the development of Monju started.

Since the beginning of the Monju project, numerous achievements were made through design, construction, operation, maintenance, and other activities over half a century as a prototype reactor following the Experimental Fast Reactor Joyo. Meanwhile, as engineers who have been engaged in the Monju project retire or leave JAEA, it is necessary to systematically collect the experience, findings, achievements, and other relevant information gained throughout the project to prevent them from being scattered and lost, and to document the information for future generations as important records and assets.

At this time of significant change in the direction of the project, it was determined to publish the present report, “Prototype Fast Breeder Reactor Monju – Its History and Achievements –”, to summarize the technological achievements obtained in the Monju project.

There is no change in Japan's policy to steadfastly maintain its nuclear fuel cycle program. Nuclear energy continues to be an essential as well as sustainable energy source that can help address global warming. The FBR cycle is also effective for reducing the environmental burden from high-level radioactive waste, and hence FBR research and development activities will continue.

We believe that the achievements acquired in the Monju project will be reflected in future FBR development and expect that this report will serve as a valuable reference.

I would like to express my sincere gratitude to all those who supported and gave guidance in the project. Lastly, I would like to express my deep gratitude to all those who have given their time, energy and talent to create the foundation for FBR development.

March 2019

Toshio KODAMA

President

Japan Atomic Energy Agency

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Introduction

This report summarizes the history and technological achievements of the Prototype Fast Breeder Reactor Monju over half a century, from the start of research and development (R&D) with the foundation of the Power Reactor and Nuclear Fuel Development Corporation (PNC, currently JAEA) in 1967, to the Japanese Government's decision to decommission Monju in late 2016.

It is heart-rending that Monju, the result of a great endeavor by experts from many organizations in industry, academia, and government, is being decommissioned without completing full-power operation. This report summarizes the knowledge and experience from the technological perspective, without addressing the social circumstances or political perspectives.

In Japan, a country with extremely scarce natural resources (exhaustible energy resources), the development of the nuclear fuel cycle enabling semi-permanent stable energy supply has been promoted. The fast breeder reactor (FBR)[1], which is a central element in the cycle, has been developed mainly in advanced countries from the early days of nuclear energy development aiming for the effective use of uranium resources.

The Japan Atomic Energy Commission (JAEC) formulated a basic policy in May 1966 to comprehensively promote the development of a sodium-cooled FBR with plutonium-uranium mixed oxide (MOX) fuel as a national project, including the construction of experimental and prototype reactors based on domestic technologies.

According to the policy, the Experimental Fast Reactor Joyo that preceded Monju was developed as the first FR in Japan. The Japan Atomic Energy Research Institute (JAERI, currently JAEA) started the conceptual design of Joyo, and then the PNC took over the detailed design. Construction started at the PNC's Oarai Engineering Center (OEC, currently Oarai Research and Development Institute), Ibaraki prefecture, in 1970, and the initial criticality was attained in 1977. In Joyo, a wide variety of design confirmation and plant performance tests were conducted.

At that time, Japan had little technology for and experience in handling a large amount of high-temperature liquid sodium, and hence, facilities related to sodium technology were constructed at the OEC together with Joyo. Using the facilities, a wide variety of R&D activities were conducted, ranging from fundamental studies on the handling and physical properties of sodium to engineering studies on the development of new sodium components. For large-scale sodium components such as circulation pumps and heat exchangers in particular, a wide variety of tests, from elemental to full-model tests, were conducted.

MOX fuel was developed at the Plutonium Fuel Development Facility of PNC's Tokai Works, where fundamental tests, fuel fabrication technology development, and fuel design were conducted. Based on these experiences, the Plutonium Fuel Production Facility was constructed in 1988 to fabricate the Monju fuel. In parallel, facilities designed for post-irradiation examination (PIE) of fuels and materials were constructed at the OEC, and PIEs of fuels irradiated in foreign FRs and Joyo were conducted to improve fuel performance such as fuel integrity and reliability.

These R&D activities were carried out under an all-Japan cooperation scheme,

[1] The terms "fast breeder reactor" (FBR) and "fast reactor" (FR) are not clearly distinguished in this report. They differ only in the reactor core configurations, but are the same as a nuclear reactor.

gathering experts from industry, academia, and government. All the R&D achievements, including experience gained in Joyo, were reflected in the design of Monju. In addition, a series of safety technology guidelines for FRs were developed. These included Japan's first safety design policy, elevated temperature structural design policy, and seismic design policy, all of which are now important bases for future FR development both domestically and internationally.

The construction of Monju started in October 1985 in Shiraki, Tsuruga city, Fukui prefecture. Initial criticality was achieved in April 1994, and the first connection to the power grid was achieved in August 1995. Through 40% power operation, the technological base of design and manufacturing of FRs was developed in various fields such as core and fuel, components and systems, and sodium handling, as well as industrial (manufacturer) technologies, such as large-scale component manufacturing technologies.

In December 1995, during the System Startup Tests (SST), a sodium leak accident occurred in the secondary heat transport system that resulted in reactor shutdown (i.e., the Secondary Sodium Leak Accident). After completion of the investigation of cause and careful government-level discussion of development strategy, modification work for measures against sodium leak was carried out. In May 2010, Monju restarted and achieved criticality to resume SST.

In addition to the Secondary Sodium Leak Accident, Monju experienced In-Vessel Transfer Machine (IVTM) dropping (2010) and other incidents. The investigation of cause and measures taken for hardware and software are also achievements that contribute to the establishment of safety improvement technology toward future FRs. Representative achievements include the clarification of two types of steel corrosion mechanisms during sodium leak and the development of the design guides of Japan Society of Mechanical Engineers based on the findings from hydraulic oscillation tests on the thermocouple sheath.

As mentioned above, the level of FR technology of Japan was greatly improved from nearly-zero to a leading global level through the development of Joyo and Monju, including the development of technological infrastructure, the cultivation of human resources, and the systematization of technological standards.

In December 2016, the Government announced its “Fast Reactor Development Policy”, under which it was decided that Japan would continue FR development for the future, but that Monju would be transferred to decommissioning because of significant uncertainties in the schedule and economic prospects before restart. These included the response to the New Regulatory Standards. With this government decision, it became practically impossible to achieve the original goals expected for Monju such as the confirmation of performance in the rated power operation, and the accumulation of knowledge and experience in long-term operation and maintenance for future FRs. The decision also made it impossible to acquire data useful for the reduction of environmental burden of high-level radioactive waste, the development and validation of high-burnup fuel, and innovative maintenance technologies for improving the economy of future FRs.

In 2018, a “Strategic Roadmap” for FR development was formulated, which points out the necessity of fully using the knowledge and experience acquired in Monju in order to introduce technological innovation aiming for a higher level of reactor technology. We eagerly hope that documenting the development processes and achievements of Monju will convert the accumulated technological findings and experience into explicit knowledge, and thereby help address the energy security issue in Japan through acceleration of the development and actual commercialization of FRs.

Kazumi AOTO
Director General
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Japan Atomic Energy Agency

1. History and Achievements

- In 1966, the FBR development program was officially launched in Japan, a country that is poor in natural energy resources. It was decided that FBR development should be based on domestic technologies, joining all-Japan efforts in a collaborative regime of industry, academia and government.
- FR related R&D activities covered a broad area from the basic fields such as nuclear data and material development to the engineering fields of component development, sodium technology, and operator training. The technological infrastructure has been established and expanded with many new research facilities.
- The design and construction of the prototype reactor “Monju” was based mainly on the domestic R&D results, and it successfully achieved initial criticality and power generation. Operating experience up to 40% power and the lessons learned from various incidents and technological challenges have been accumulated for the improvement of safety and future FR development.
- Through these activities, a world-class FR technology base has been built in Japan.

1.1 Beginning of the Monju project

In the early 1960s, while Western countries actively promoted the commercialization of light water reactors (LWRs) and the development of FBRs, Japan had just started an early basic study on FBRs.

In 1964, the JAEC established the Advisory Committee on Power Reactor Development to discuss an overall picture concerning the research, development, and utilization of nuclear energy in Japan. The key subject discussed was the way to develop nuclear energy in Japan. Discussions included how the LWR should be introduced, how the FBR and an advanced thermal reactor (ATR) should be developed, and how the nuclear fuel cycle should be developed. The discussions lasted for one and a half years, and during this period the Fact-Finding Mission on Power Reactors was dispatched to European countries and the U.S. for one month. The Mission concluded the necessity of: firm national determination to cultivate the ability to compete with the leading countries, enormous investment of financial and human resources, consistent development of nuclear fuel policy, and steps for the development of experimental, prototype, and demonstration reactors, as well as the importance of basic research. The Mission also reported that Japan as a latecomer far behind the U.K., the U.S., France, etc., should efficiently conduct, in a preparatory stage for a prototype reactor, the construction of an experimental reactor as early as possible and pursue the development of cooling systems and safety technologies through large-scale mockups by bringing together the nation's talent and resources and taking full advantage of international cooperation.

In May 1966, the JAEC formulated the "Basic Policy for Power Reactor Development", which stated that the domestic nuclear fuel cycle should be established to maintain sound development of national economy and energy security, that FBRs could basically solve the nuclear fuel resource problem and become the mainstream of nuclear power generation in the future, and that, accordingly, FBRs should be developed efficiently with domestic technologies by accumulating base technologies and through international cooperation. Since FBR development was a large-scale project being organized for the first time in Japan and a unique organizational structure that included the active participation of industry, academia, and government was required, it was decided to establish, by fiscal year (FY) 1967, a special governmental corporation responsible for the development of the prototype FBR and ATR.

In October 1967, the Power Reactor and Nuclear Fuel Development Corporation (PNC) was founded, and the basic policy on the tasks of the PNC was defined by the Prime Minister in March 1968. The task related to FBR development was described as follows:

> *-The goal is to develop a sodium-cooled FBR using MOX fuel. Assuming that a prototype reactor with an electric power ranging from 200 to 300 MW would reach criticality in around FY 1976, development of the specific construction plan should be based on the review of R&D achievements and technological trends in foreign countries.*

It was also defined that: the development should be managed with a collective system in which the PNC takes responsibility as the key organization, the national budget should be the main financial resource, at least half of the construction cost is expected to be shared by the private sector, and adequate human resources should be ensured through participation by the relevant organizations.

FBR development at the PNC required comprehensive engineering capabilities, and an all-Japan cooperation regime was established by a variety of personnel, including experts from universities, JAERI, electric utilities, and manufacturers. FBR technologies spread over various new fields and technical elements with little engineering experience in Japan. These included high-temperature sodium, plutonium fuel, and fast neutrons. Thus, R&D activities and construction of an experimental reactor were essential to mastering the relevant elemental technologies for application to a plant system of Monju.

In April 1970, it was announced that the experimental FR would be named "Joyo", the prototype FBR would be named "Monju", and the prototype ATR would be named "Fugen" at the opening ceremony of the OEC. The two prototype reactors were named after Monju and Fugen Bodhisattvas, in the hope that nuclear energy would be overseen by their wisdom and mercy, and thereby utilized for the welfare of the population. The name of the experimental reactor Joyo was taken from the old name for the Oarai area where the reactor is situated.

1.2 Significance and roles of Monju

It was a great challenge for Japan to construct the prototype FBR because the technological infrastructure for FBR development had not yet been established. Therefore, it was necessary to determine a design concept that was technologically feasible and could be constructed in Japan, develop unique technologies related to specific design and manufacturing, embody the concept into an actual reactor plant, and design, construct, and operate the reactor. Thus, Monju had the role of exploring and paving the unknown road to the commercialization of FBRs, which would be driven by Monju development.

After completion of construction, Monju achieved criticality and connection to the power grid. Subsequently, the Long-term Plan for Research, Development, and Utilization of Nuclear Energy formulated in 2000 stated that the priority of Monju should be the demonstration of reliability as a power plant and the establishment of sodium handling technology, and on a long-term basis, that Monju should be effectively used to demonstrate elemental technologies aimed at FR commercialization, and to burn minor actinides or transmute long-lived fission products as a facility where fast neutrons can be provided. By this time, FR development abroad had slowed, and the target year of FR commercialization in Japan became obscure. In this circumstance, Monju was positioned as a key facility for R&D on FBR cycle technologies.

The Accident at the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company (hereinafter called the "1F Accident") that occurred in 2011 was a turning point. The national energy policy was thoroughly reviewed, but it was positively concluded that Monju R&D should be continued. In September 2013, the Monju Research Plan Working Group formed in the Ministry of Education, Culture, Sports, Science and Technology (MEXT) established the "Monju Research Plan", a more specific R&D plan using Monju, in which short-term research targets are set and the achievements are evaluated to determine whether or not the research is further continued.

1.3 History of Monju

The history of Monju development is shown in Fig. 1-1. In March 1968, the Prime Minister issued a basic policy on the tasks of the PNC as mentioned before. It was then necessary to determine the concept of a technologically feasible prototype reactor. In the process, a series of design studies were repeated in cooperation with the manufacturers to embody the concept of plant systems and major components. In parallel, R&D activities for Monju were conducted at the OEC (Photo 1-1), including mockup tests for major components and development of analysis tools, while being confirmed by various specialist committees of external experts.

The plant concept and construction plan for Monju were checked and reviewed by the JAEC in 1975, and the conclusion was reached that the plan was appropriate.

Besides, Joyo, which was constructed before Monju, achieved initial criticality in 1977, and subsequently, accumulated good operating performance. The experience obtained through Joyo operation were very valuable and useful for the development of Monju in terms of technology and human resource development.

Geological and environmental surveys of the construction site were conducted in Shiraki of Tsuruga city, Fukui prefecture. After approved by the local governments, the Application for the Reactor Installation Permit was submitted in December 1980. Based on the progress in the Safety Review of Monju and approval by the local governments, the Government approved the site and construction of Monju at a Cabinet Meeting in May 1982. This was the green light for construction although some licensing procedures were required thereafter.

Construction started with preparatory work such as road and tunnel access to the site. The main work on the site started in October 1985, and in about five and a half years, the installation of components was as scheduled completed in May 1991.

As commissioning before fuel loading,

the Comprehensive System Function Tests, including sodium charging into the systems, were conducted for about two years, the loading of core fuel subassemblies started in October 1993, and the initial criticality was achieved at 10:01 on April 5, 1994. This very moment was shared by FR experts from abroad and mass media representatives in the central control room. The media reported this commemorable milestone to audiences around the globe.

In SST started after initial criticality, reactor physics tests were conducted at a low power level. In February 1995, the system temperatures were increased with the start of the nuclear heating test, 40% rated reactor power was produced in June, and power generation and transmission were achieved on August 29 for the first time by Japan's FR.

On December 8, 1995 during SST, the Secondary Sodium Leak Accident occurred. The Accident caused no significant

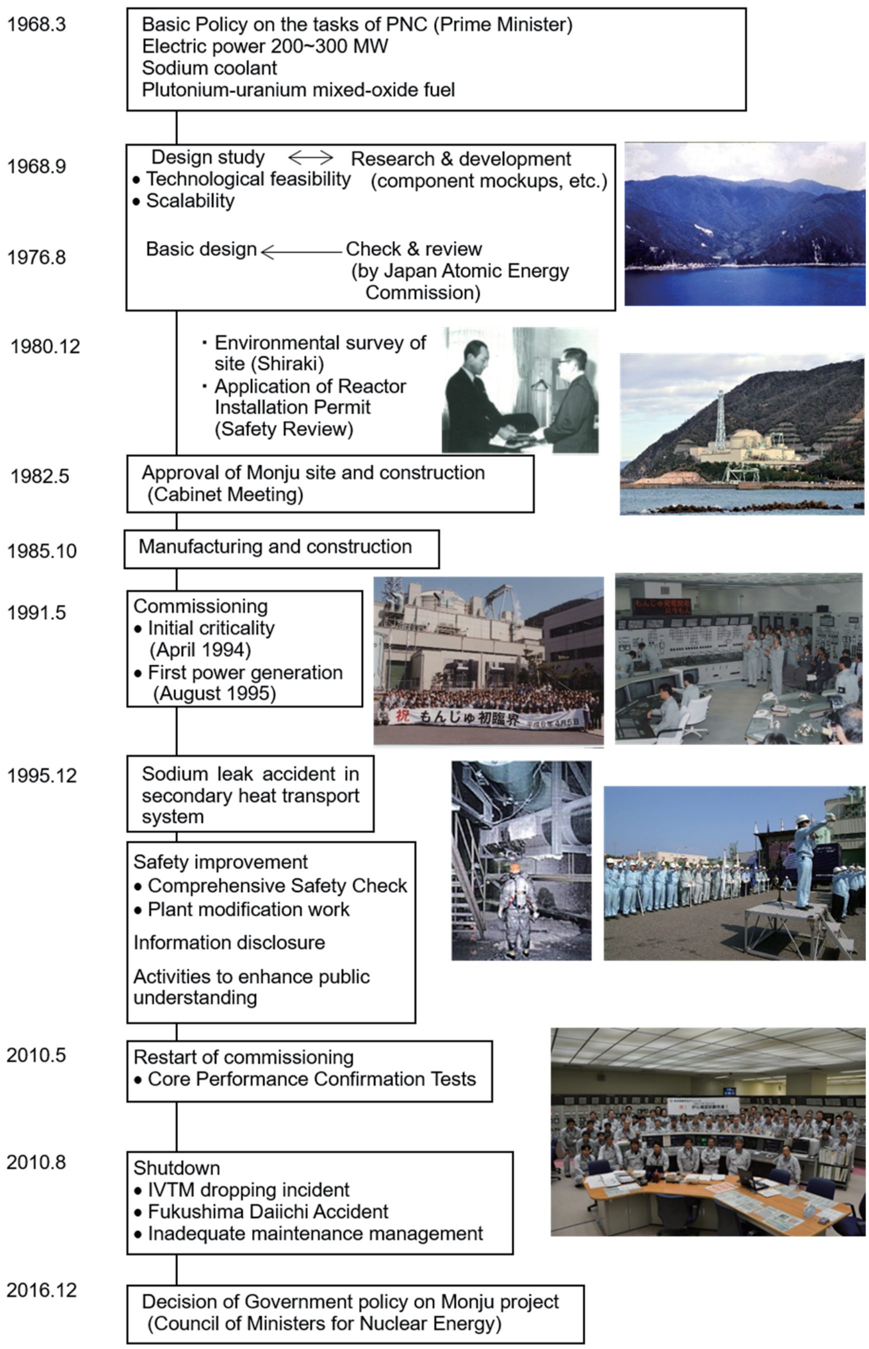


Fig.1-1 Main flow of Monju development

Shiraki area, Tsuruga city, Fukui prefecture

Oarai area, Ibaraki prefecture

Tokai area, Ibaraki prefecture

Photo 1-1 R&D centers for Monju development

radiation exposure and was rated at International Nuclear Event Scale (INES) Level 1. However, since there were administrative problems, including inappropriate information disclosure, it took more than 14 years before Monju was restarted.

During this period of long-term reactor shutdown, various activities took place. These included investigation of the cause of the Accident, Comprehensive Safety Check, and seismic evaluation, as well as modification work to improve safety, which included the enhancement of measures against sodium leak. Proactive information disclosure and public communication activities focused on the local communities in Fukui prefecture were promoted.

On May 6, 2010, SST were resumed, and valuable data on the core characteristics of the minor actinide-containing core were obtained. Subsequently in August, after completion of refueling necessary for the 40% power test, the IVTM was accidentally dropped and recovery efforts took a few years. Furthermore, the 1F Accident occurred and Monju was forced to stop again for many years.

In November 2012, inadequate maintenance management became an urgent issue to tackle and efforts were made to rectify the situation. However, while improvement activities were under way, the Nuclear Regulation Authority (NRA) issued a recommendation to the MEXT to review the operating organization of Monju. In December 2016, the Council of Ministers for Nuclear Energy decided that Monju would be transferred to decommissioning because of significant uncertainties in the schedule and economic prospects before restart, such as the response to the New Regulatory Standards.

1.4 Achievements of Monju

Monju is an FBR plant that was designed and constructed toward the commercialization of FRs considering safety and reliability with large margins as a reactor in the R&D stage. Accordingly, it was expected to validate the design and idea adopted through its construction and operation, and to accumulate operation and maintenance experience for future FRs.

1. History and Achievements

Technological achievements made through the development of Monju are summarized in Figs. 1-2 and 1-3. Industrial FR technologies were acquired through design and manufacturing experience. Through commissioning tests, highly accurate FR core design technology was developed and validated. In addition, the elevated temperature structural design policy and methods were developed in consideration of the characteristics of sodium-cooled reactors, and the concept of safety design of FR has been established. Also acquired was high-precision manufacturing technologies for large sodium components, including the reactor vessel (RV), circulation pumps, and steam generators (SGs).

On the other hand, since the operation of Monju was ceased in the middle of SST, performance confirmation is limited to tests at partial power levels, and no plant operating experience at the rated power were obtained. In other words, the goal of developing a technological knowledge base, as a prototype reactor, on the operation and maintenance experience was only partially accomplished.

[Loop-type FR technology]
The full-scale prototype FR plant with power generation equipment was successfully designed, manufactured, and constructed based on Japan's domestic technologies, and demonstrated the feasibility and licensability of loop-type FR systems.

[FR technologies of a world level]
World leading FR technologies, on safety, reactor core, fuel, systems and components, sodium handling, etc., have been developed through the design and construction of Monju.

[Technological base]
The R&D infrastructure has been developed for Monju on reactor and fuel technologies, and thereby human resources and intellectual properties have been accumulated. Also developed are technological policy and knowledge base, such as safety design philosophy and elevated-temperature structure design guides.

[Plant operating experiences]
Experiences in accidents and failures, including sodium leak accident and minor failures, have been accumulated, and thereby issues to be improved are extracted for future FR comerciali-zation.

Fig.1-2 Summary of Monju achievements

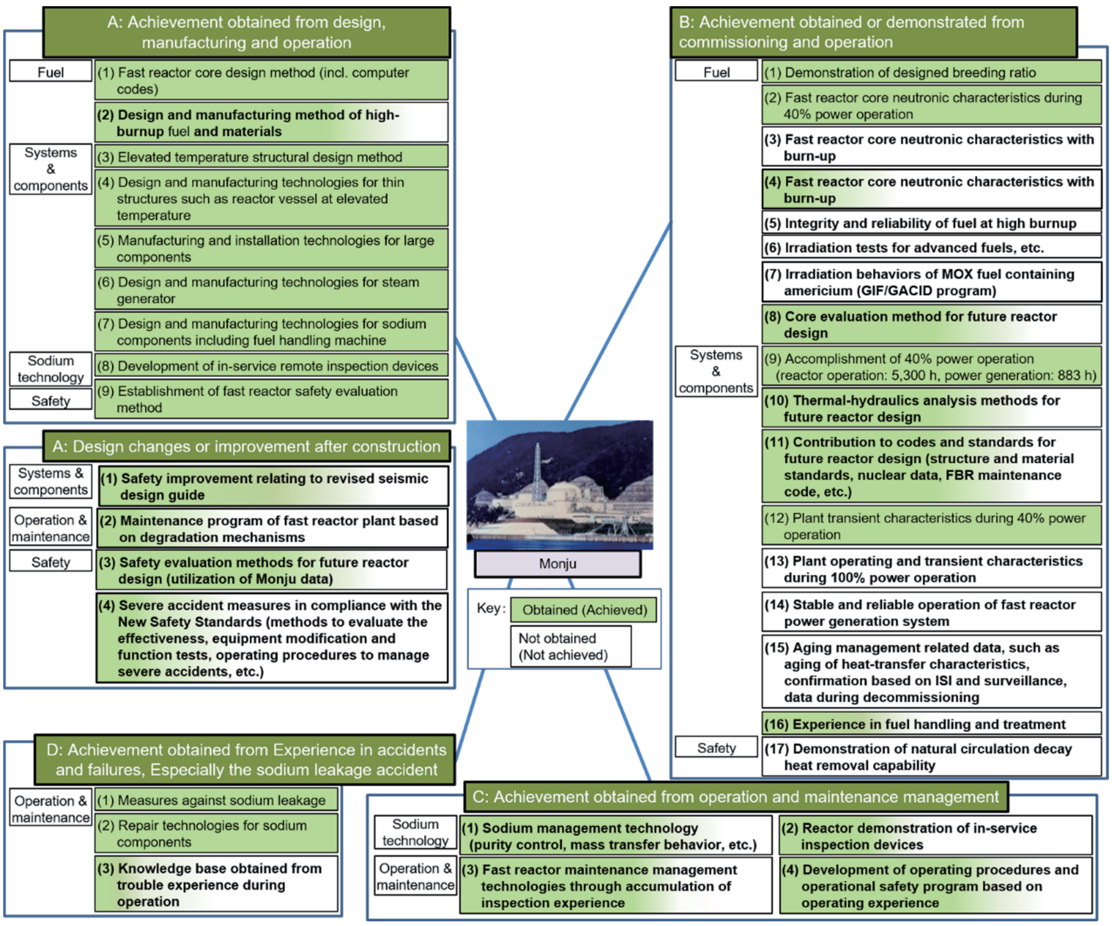


Fig.1-3 Major technological achievements of Monju (white parts are unfinished)

2. Design and Construction

- Monju design and construction was based on Japan's domestic technologies with the concerted effort of the relevant industry, academia, and government organizations while the technological infrastructure of Japan FR technologies such as R&D facilities and fuel fabrication plants were developed and the level and range of FR-related technologies were raised and enlarged.
- In the design process, various R&D activities such as tests to develop major components, clarification of phenomena and behaviors, and development of evaluation methods were carried out in parallel to pursuing a feasible plant concept, and thereby, a loop type FR concept was developed as an FR power plant.
- In the construction process, manufacturing, shipment, and on-site work proceeded as scheduled although an unprecedentedly large variety of components had to be fabricated with high precision.
- These design and construction technologies are comparable to the level of technology of countries advanced in FR development, namely, Japan established world-class FR technologies.

2.1 Major specifications

One of the roles of the prototype reactor is to identify technologies applicable to commercial FBRs. Thus, the major specifications of Monju, as listed in Table 2-1, were selected based on Japan's own philosophy by evaluating the design study and the related R&D as well as the information on the preceding foreign prototype FBRs, expecting future possible technological advancement.

Table 2-1 Major specifications of Monju

Reactor type	Sodium cooled loop type
Thermal power	714 MW
Electric power	~280 MW
Fuel	Plutonium-uranium mixed oxide
Burnup of fuel	80 GWd/t (average of discharged fuel)
Fuel cladding	SUS316-equivalent steel
Cladding temperature	Max 675°C (mid-wall)
Breeding ratio	1.2
Number of cooling loops	3
Location of circulation pump	Hot leg installation
Reactor temperature	397°C / 529°C (inlet / outlet)
Secondary sodium temperature	505°C / 325°C (hot leg / cold leg)
Main steam conditions	127 kg/cm^{2}G, 483°C
SG type	Helically-coiled, separate type
SG layout	Concentrated arrangement
Refueling scheme	Single rotating plug with a fixed arm
Refueling interval	~6 months
Decay heat removal	Cooling in the secondary loop
Method to ensure coolant level	Pipe routing at high elevation with guard vessels

2.2 Plant concept and design study

A bird's-eye view of the entire plant is shown in Fig. 2-1. A design study of Monju started in 1968, when the PNC asked five domestic nuclear manufacturers (Sumitomo, Toshiba, Hitachi, Fuji, and Mitsubishi) to develop the Preliminary Design of Prototype Fast Breeder Reactor, and each company created independent designs based only on the basic specifications of several items such as the electric power and coolant (Table 2-2).

The development of Monju started under the basic policy to bring a sodium-cooled, MOX-fueled prototype FBR with an electrical power of 200 to 300 MW into criticality by around 1976, although there was little engineering experience with FBRs in Japan. The first goal was to select a basic concept conceiving the ideal image of Japan’s commercial FBRs. Basic design concepts such as loop-type, cold-leg pump, reheating cycle, integrated once-through helically coiled SG, refueling with single rotating plug with a fixed offset arm were extracted through evaluation and review of the design proposals made by the five manufactures.

After completion of the Preliminary Design, Monju design progressed to Phases 1 through 3 in series, followed by the Adjustment Design started in 1974. In 1977, the Manufacturing Preparation Design was started with a focus on preparation of the

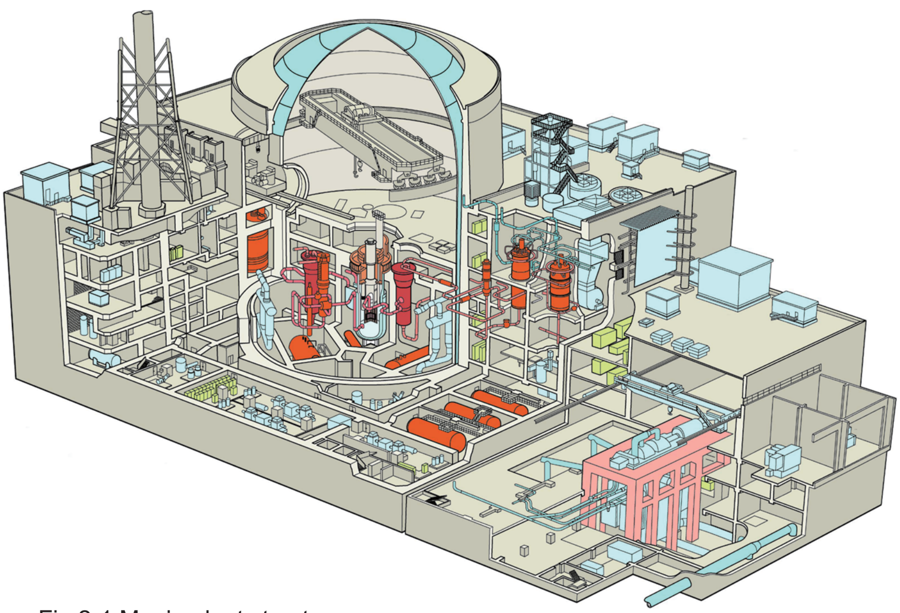


Fig.2-1 Monju plant structure

Table 2-2 Major design phases of Monju

Preliminary design	FY1968	**[Selection of major concepts]** Five manufacturers in Japan performed the preliminary design for an electrical power of 300 MW, including the selection of reactor type, systems and components, and materials. Based on the results, major specifications were determined.
Prototype reactor phase 1 design	FY1969	**[Conceptual design of reactor core]** Based on the determined major specifications, comparison was made among system concepts, loop-type systems, and major components, and various parameter surveys were conducted.
Monju phase 1 design	FY1970	**[Design of major components]** The reactor was named "Monju". Focus was placed on the design of the main systems. Reactor structure design, such as nozzle position, seismic study, and core design were performed in parallel.
Monju phase 2 design	FY1971	**[Design of entire plant]** Focus was placed on plant consistency and safety to achieve harmonized plant design.
Monju phase 3 design	FY1972–FY1973	**[Plant layout and safety design concept]** Examination of single wall piping (PHTS pipe routing at high elevation), auxiliary cooling system, and reheat/non-reheat system. Design was partially refined in consideration of R&D results and foreign information.
Adjustment design	FY1974–FY1976	**[Licensable and reasonable design, summary of conceptual design]** Planning of further required R&D items, and design to confirm plant viability.
Manufacturing preparation design	FY1977–FY1979	**[Summary of R&D, refinement of design specifications, analyses of important items]** Design prior to the transition from conceptual design to manufacturing design (major specifications were almost fixed in this stage)
Safety review, preparation of manufacturing	FY1979–FY1983	**[Design and analysis on safety review, design adjustment]** Analyses for Safety Review, design adjustment, examination of specific issues for each design, condition setting prior to actual design such as thermal transient conditions.

Application for the Reactor Installation Permit, finalizing the design to confirm that the Permit could be obtained and the construction cost would fall within a range that would allow the contracts to be ordered. Meanwhile, in 1975, the JAEC checked and reviewed the Monju construction plan and concluded that the plan was appropriate.

In the design elaboration process, layout planning of components, piping, wiring, and ducts was performed in further detail and some specifications were changed as follows:

- Elimination of spent fuel in-core storage,
- Installation of the auxiliary cooling system in the secondary heat transport system (SHTS),
- Adoption of horizontal pipe routing at high elevation for the primary heat transport system (PHTS) hot-leg piping,
- Elimination of core clamping structure,
- Change from the selector valve to tagging gas method for failed fuel detection, and
- Elimination of SG reheater.

In the above-mentioned design study series, Mitsubishi Heavy Industries, Ltd. was designated a managing company in charge of coordination among the manufactures. Meanwhile Toshiba and Hitachi were designated the managing companies for Joyo and Fugen, respectively. In April 1980, Fast Breeder Reactor Engineering Co. (FBEC) was established to be in charge of management, including the coordination of design activities.

2.3 R&D centered at the OEC

There was little experience in handling a large amount of high-temperature liquid sodium in Japan when Monju design work started. Facilities to develop sodium technologies were constructed at the OEC, and various research activities ranging from basic to engineering scales were conducted. The first facility, which was constructed in 1969, was the Sodium Thermal Hydraulic Test Facility, in which 17 tons of sodium are handled, to learn sodium handling technology and understand the characteristics of sodium components on a small scale. Subsequently, research activities were expanded to the basic properties, thermal hydraulic characteristics, and compatibility with structural materials, which were intended to confirm the feasibility of using sodium as coolant. Furthermore, various tests with sodium were conducted consecutively to confirm the sodium purity control technology and the behavior of activation and corrosion products in the primary systems.

After acquiring this experience, R&D of components for Joyo started in 1970. Compared to Joyo, Monju reactor power is seven times higher, it has a higher reactor outlet temperature, and it includes a power generation system. Therefore, it was necessary to scale up the individual components and develop new component systems. Full-scale mockup models were manufactured for active components such as the control rod drive mechanism (CRDM), fuel handling machine, and pumps. The scaled or partial models were manufactured for the SG. A comparison of mockup models between Joyo and Monju are listed in Table 2-3. These mockup tests, including experience in manufacturing, were effectively reflected in the subsequent design and manufacturing of actual Monju components.

The experimental reactor Joyo achieved initial criticality in 1977. Following six cycle operations at the rated power of 75 MW, the Joyo core was converted to the irradiation core (MK-II), which has been used as an irradiation bed for various types of fuel and material, including the fuel for Monju since the start of operation at the rated power of 100 MW in 1983. The technologies and experience accumulated in Joyo, which was designed, constructed and operated with domestic technologies, were effectively reflected in the design, construction and operation of Monju (Table 2-4). Many engineers and operators educated and trained in Joyo were reassigned to the Monju project.

The Monju SG is a separated once-through type consisting of an evaporator and a superheater, equipped with helically coiled heat transfer tubes. The SG technology was developed at the OEC from a basic research phase with a small-scale SG of 1 MW to one of the world's largest SG test facilities of 50 MW (50-MW SG), equivalent to about one fifth of the Monju SG. R&D activities and test operations for a cumulative time of 30,000 hours efficiently yielded demonstration data related to structure and material, operation and handling, maintenance and repair, and safety and reliability. Concerning a possible water leak, a wide variety of tests and analyses were conducted and measures against water leak accident in the Monju SG were developed. Concerning sodium leak and fire, a series of simulation tests were conducted up to 70 times. R&D activities were also devoted to the development of an RV inspection robot, an in-service inspection device designed to confirm the in-

Table 2-3 Comparison of mockup models of Joyo and Monju
(Ratio of mockup model to actual core)

		Joyo MK-II	Monju	Remarks
Specifications	Thermal power	100 MW	714 MW	
	RV outlet temperature	500°C	529°C	
	RV size	D: 3.6 m H: 10 m	D: 7.1 m H: 18 m	
	Generator	No	Yes	
RV structure components	RV	1/1	Water test: 1/1 (1/3 sector) 1/2, 1/5, 1/2.25, 1/6 Sodium test: 1/6, 1/10	Focus on thermal transient and thermal stratification in the upper plenum
	Shield plug	1/1	D: 1/2.5	Integrated thermal insulation test
	Core internals	1/1	Water test: 1/2	Focus on flow rate allocation
	Upper core structure	1/1	1/1 (1/3 sector)	Water flow test
	Thermal striping test	—	Water test: 1/1 Sodium test: 1/1	
	CRDM	1/1	1/1	Water / Na test
Coolant system	Main circulation pump	1/1	1/1	Water / Na test Smaller impeller in Na
	Intermediate heat exchanger (IHX)	1/50 (exchanged heat)	Water test: 1/1 (1/6 sector) 1/2 Na test: 1/2.5 (thermal shock)	Water test: tube bundle 1/1, inlet and body 1/2 Na test: heat transfer tube 1/1
	SG	No	1/5 (exchanged heat) H: 4/5, D: 1/3	heat transfer tube 1/1, number 1/5 (for 50MW No.2)
Fuel Handling system	Fuel exchanger	1/1	1/1	
	Fuel transfer machine	1/1	1/1	Except fuel transfer car
	Ex-vessel fuel storage tank	No	1/3 (1/6 sector)	

tegrity of major components and equipment, as well as the measurement technologies, including the electromagnetic flowmeter for sodium, unique to FRs.

Structural materials of Monju are used at temperatures exceeding the temperature stipulated in the structural design standards for LWRs (i.e., 425°C for austenitic stainless steel). Thus, the draft of Elevated Temperature Structural Design Policy for Monju was developed, and thereby material strength standards and design evaluation methods were created and improved through various types of structural material and strength tests.

Concerning safety, the technological bases for safety design and evaluation of Monju were provided by various research activities on: sodium leak and fire, sodium-water reaction, thermal hydraulic characteristics of sodium during severe accidents, reactor safety research, including in-pile tests performed through international cooperation, development and improvement of the safety analysis computer codes, and probabilistic risk assessment study.

Although Japan started FR R&D efforts ten to twenty years behind the advanced Western countries, the OEC has developed in a short time to become a center of excellence for FR R&D. Many valuable R&D achievements have been produced, including the criticality of Joyo and demonstration of the high reliability of the 50-MW SG. FR technology in Japan has become comparable to the technological level of leading FR countries.

Concerning fuel and material, cladding material was developed aiming at a core-averaged burnup at discharge of 80 GWd/t through R&D activities including irradiation

Table 2-4 Reflection of Joyo achievements to Monju

	Items contributed through Joyo	Items directly reflected	Common and base technology
1. Plant / general items	a) Operation and maintenance instructions b) Operator training simulator c) Operation aid system d) Maintenance aid system e) CV-LRT standard procedure f) Maintenance criteria g) Experience exchange with EBR-II and FFTF h) Experience exchange with Rapsodie and Phenix i) Experience exchange with KNK-II	a) Construction and operation b) Methods in SKS/SST c) Guidelines, standards d) FR system reliability database e) Natural circulation evaluation	a) Operation and maintenance training system b) Reduction in exposure focusing on corrosion products c) Purity control of sodium d) Liquid waste disposal system e) Joint research on decommissioning of Rapsodie f) Seismic response analysis g) Systematization of operation and maintenance technologies
2. Core and fuel	a) Evaluation of reactivity coefficients b) Hot channel factor c) Service life extension of core elements d) Vented-type control rod e) Irradiation of dummy failed fuel f) Nuclear material accountancy g) Rationalization of fuel design	a) Irradiation at high linear heat rate (465 W/cm) b) Irradiation of high burnup fuel (91 GWd/t) c) Irradiation of material at high fluence (2.3×10^{23} n/cm^2) d) Irradiation of fuel under ramp power (50%/2h) e) Long-life control rod (2×10^{22} cap/cc)	a) Dosimetry technology b) Decay heat evaluation of spent fuel c) On-line instrumented irradiation technology d) Power-to-melt tests for high burnup fuel e) Irradiation of high linear power fuel (with hollow pellets) f) Irradiation of ferritic steel cladding (Irradiation exchange with FFTF, up tp 3×10^{23} n/cm^2)
3. Components and systems	a) Reduction of thermal deformation of pump (convection suppressing in gas annulus region) b) Behavior of sodium vapor deposition c) Compact and high-capacity cold trap d) Anomaly monitoring of rotating component e) Inspection robot for annulus of double tube f) Material surveillance	a) Lubricity/durability of mechanical snubber b) Test irradiation for RV material surveillance	a) Evaluation of heat dissipation from piping b) Irradiation of cobalt-free material c) Evaluation of main piping and components made of Cr-Mo steel d) Trap of corrosion product e) Trap of cesium f) Underwater storage of fuel without canning g) Sodium cleaning
4. Instrumentation and control	a) Plant stability evaluation b) Gamma-ray monitoring in cover gas c) Automatic plugging meter d) Failed fuel detection system e) Measurement of thermal displacement of piping f) High-precision sodium level meter	a) Tag gas behavior analysis b) Characteristics of Kr adsorption bed c) Wide-range neutron monitor d) Flowmeter at fuel subassembly outlet	a) Temperature measurement at fuel subassembly outlet b) Calibration of flowmeter in service c) Aging characteristics of thermocouple d) Optical transmission technology

in foreign reactors. The design of fuel subassembly structure was finalized by repeating the development procedure five times; namely, trial manufacturing followed by hydraulic and strength tests of fuel subassemblies, etc. At the Plutonium Fuel Production Facility of the Tokai Works (currently Nuclear Fuel Cycle Engineering Laboratory), plutonium handling and fabrication technologies for MOX fuel have been developed.

In the field of reactor physics, various research topics were addressed in a cooperative framework with domestic institutions, universities, and manufacturers, including contract research with JAERI using the Fast Critical Assembly (FCA), and the results were accumulated.

International cooperation was also used effectively for technical exchanges with countries advanced in FR development and for reactor experiments that were difficult to conduct in Japan. Such cooperation includes fuel irradiation in foreign reactors, Operational Reliability Testing for FR fuel performed at the U.S. EBR-II, and in-pile safety tests at the French CABRI reactor. In addition, a series of Monju core simulation tests (the MOZART project) using the U.K. critical assembly ZEBRA was conducted for one and a half years, and the results were reflected in the Monju design. The results also contributed to the improvement of FR core characteristics and analysis accuracy. The MOZART project received the Atomic Energy Historic Award from the Atomic Energy Society of Japan in 2017.

2.4 Reactor Installation Permit and Safety Review

On December 10, 1980, the Application for the Reactor Installation Permit was submitted to the Prime Minister (the then responsible minister for Science and Technology Agency (STA), the then regulatory agency for Monju). The Safety Review was carried out in two stages: the first-round review by the regulatory agency and the second-round review by the Nuclear Safety Commission (NSC). The first-round review by the STA took about one year. The review was made according to the guide, Safety Evaluation Policy of Liquid-Metal Fast Breeder Reactors, specifically focusing on how to deal with beyond-design-basis events having lower occurrence frequency but more severe consequences than those of design-basis events. As the result of the Review, the Application was supplemented by improving the systems important to safety, including the plant protection and cooling systems, and the evaluation results of beyond-design-basis events.

At the completion of the first-round Safety Review, Fukui Prefecture was requested to approve the construction of Monju. After receiving prior approval by the local municipalities, the Government approved the site and construction of Monju at a Cabinet meeting in May 1982.

Following the first-round Safety Review, the second-round Safety Review was performed by the NSC. The Review was completed after the review period of about one year, including public hearings held in local communities. Upon completion of the Safety Review, the Reactor Installation Permit of Monju was issued on May 27, 1983.

2.5 Contracts for construction

The construction budget for Monju was first requested in FY 1980, and a procedure for component manufacturing contracts was started. Monju was a first-of-a-kind reactor in the R&D stage and there was little experience in the estimation of the construction cost and schedule. Thus, opinions were broadly collected from the government, electric utilities, and manufacturers, and foreign cases were widely surveyed. In particular, for contracts specific to FR components, cost estimation, technological review, and volume checks were repeated several times. Eventually, it was agreed that the components contract be divided into “a blanket order covering four companies” and “individual orders” (i.e., direct and additional orders), respectively worth about 350 billion yen and 80 billion yen. The construction cost of Monju, consisting of the building structure cost and construction preparation cost in addition to the cost of the above-mentioned component manufacturing contracts, amounted to a total of about 600 billion yen.

The component manufacturing contracts were implemented in four parts. The first part of the component manufacturing contracts was implemented in January 1984, when the component manufacturing stage was started on a full-scale basis.

2.6 Construction

Following the Reactor Installation Permit, two types of licensing applications were submitted for construction. One was the “Approval of the Design and Construction Method” as a reactor in the R&D stage under the Reactor Regulation Act and the other was “Construction Plan Approval” as an electric facility for private use under the Electricity Business Act, in series and grouped by equipment.

Since no regulatory standards for the approval of the design and construction method for FRs were available, the STA set “Technical Standards for Structures” and “Technical Standards for Welding” as its bylaws for sodium-cooled FRs. For the Construction Plan Approval, “Special Design Approval” was applied for components used at high temperatures exceeding the upper limit of the LWR standard (375°C). Pre-Service and Welding Inspections were also conducted under the two approval systems.

The Monju components were manufactured in the manufacturer's factories. Since the major components are used in high-temperature sodium environments, high quality controls, such as high dimensional accuracy and low strain control, were needed throughout the manufacturing process, including machining, welding, and assembling. The manufacturers ensured “Monju-grade quality” that is especially high in the “nuclear-grade quality” ensured in LWRs. As a result, the components were shipped to the site as scheduled

Large and heavy components were delivered to the site by sea. Since the site faces the Sea of Japan, the transport and assembling processes were closely coordinated to deliver the components from April to October, when the weather conditions are mild.

The Monju construction schedule is shown in Fig. 2-2. After receiving the Reactor Installation Permit, the procedures for site preparation work, including those for the Natural Parks Act, were carried out. The construction of access roads to the site started in January 1983, the Building Certificate was issued by Fukui Prefecture in October 1985, and then full-scale construction finally started (Photo 2-1).

Photo 2-1 Praying for safety in construction

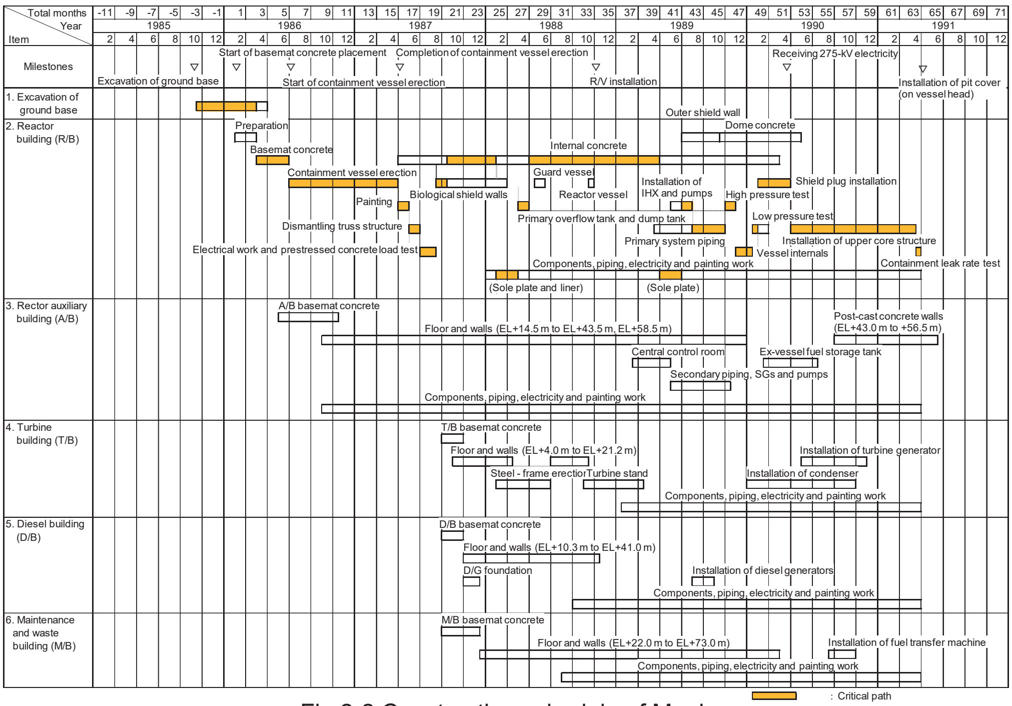


Fig.2-2 Construction schedule of Monju

2. Design and Construction

January 1983

September 1983

September 1984

September 1985

September 1986

September 1987

September 1988

September 1989

Photo 2-2 History of the plant construction

Site foundation excavation was started shortly thereafter. Mat concrete pouring for the reactor and reactor auxiliary buildings was started in February 1986, and construction of the reactor containment vessel (CV) was started in July. Large-sized steel plate blocks were assembled in a temporary factory, which was installed on site, and installation of the CV was completed in April 1987. The guard vessel was installed in June 1988 and the RV body was installed in October. Installation of a total length of four million meters of cables was accomplished within the initial schedule through strict construction management as a critical process (Photo 2-2).

The features of the site work are as follows:

- A factory to assemble and weld the lining system was placed on site to smoothly perform concrete pouring for floors and walls and lining work in the reactor building, which need complex mutual coordination. (The internal concrete work took 29 months, three times longer than that for an LWR.)
- A large side crane was adopted to assemble and install the CV with a height of 79 m (Photo 2-3).

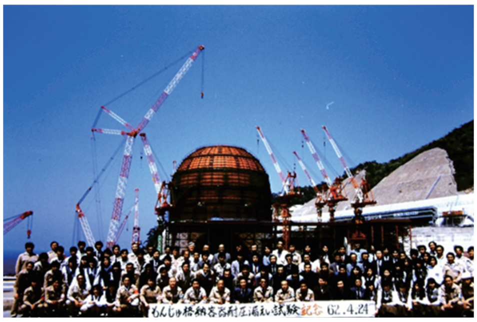


Photo 2-3 Large side crane (left behind) and tower crane (right)

- A batcher plant dedicated to pouring construction concrete (330,000 m^3) was installed on the site.
- Multipurpose gantries (up to 11 units) were installed along the building side wall. Multipurpose tower cranes (up to 12 units) were installed along the gantries and a monitoring system was installed to prevent their interference.
- The biological shielding wall installed around the reactor was made of steel plate concrete to ensure support and precision during installation of large and heavy components, including the RV (Photo 2-4).

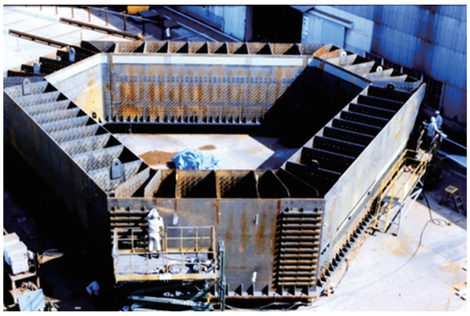


Photo 2-4 Biological shielding wall made of steel

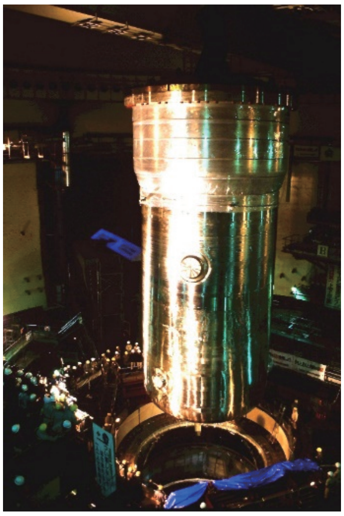
- The cleanliness of sodium components was maintained as in the manufacture's factory, considering the significance specified in the guidelines to maintain and control the cleanliness of the sodium components.
- The construction was supervised by Japan Atomic Power Co., Ltd., which has sufficient experience in constructing nuclear power plants.

Many companies participated in the construction to comprehensively advance domestic technologies. The number of contracts exceeded 40 with about 400 participating companies, and the cumulative man-days reached 4 million. Therefore, schedule management, quality control, safety management, and their mutual coordination became a major task. Fortunately, the construction work was completed as scheduled without serious incident. This was due largely to the fact that:

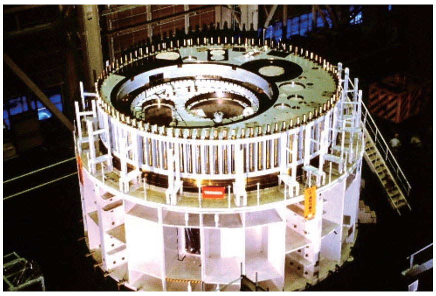
- The manufacturers were involved in the project from the beginning of the design study, and they were familiar with the design details and accumulated experience.
- Experts in a wide variety of fields such as R&D on FRs, Joyo, Fugen, LWR construction process management participated in the construction.
- The FBEC played its role as a coordinator among manufacturers in the fields of engineering and construction.
- Persons involved in the work shared the significance of Monju through activities promoted by the Safety and Health Promotion Committee.

During the design stage and Safety Review of Monju, the PNC headquarters based in Tokyo led project management. With the progress of component manufacturing, delivery and installation, the responsibility for equipment management was transferred to onsite organizations and headquarters staff was moved to the site. In addition, persons experienced in the construction and operation of Joyo, workers involved in sodium technology development at the OEC and staff of Fugen were gathered to the Monju Construction Office. Temporary staff from electric power companies and personnel to be engaged in the operation and maintenance of Monju were assigned to the site organizations after receiving technical training on FRs at the OEC. On the site, full-scale organizational structure for commissioning was prepared after completion of component installation (Photos 2-5 and 2-6).

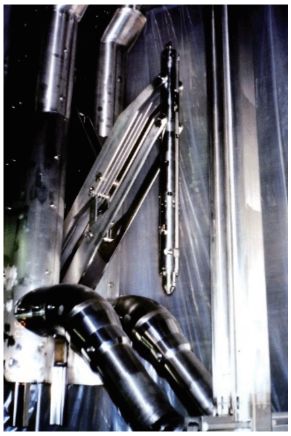
Photo 2-5 Ceremony for completion of component installation



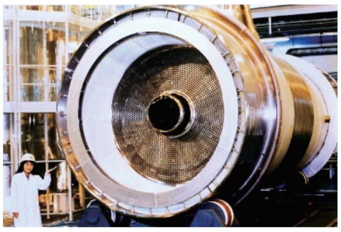
Installation of reactor vessel



Shield plug



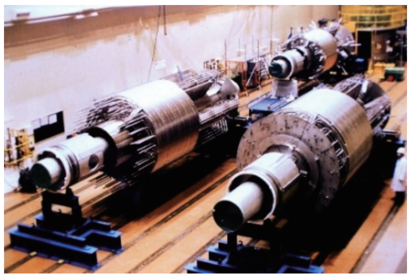
Holddown arm
(Fuel exchanger)



Intermediate heat exchanger

Ex-vessel fuel storage tank

Large sodium valve



Superheater

Photo 2-6 Major components installed