DOI: 10.15669/pnst.8.185

Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 185-190

ARTICLE

Design Policy of Pilot Plant for Accelerator-Driven System

Kenji NISHIHARA*, Takanori SUGAWARA, Masahiro FUKUSHIMA, Hiroki IWAMOTO, Ryota KATANO and Takumi ABE

Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan

A pilot plant for the accelerator-driven system (ADS) is proposed as a scaled-down version of a lead-bismuth cooled ADS with 800 MW thermal output for transmutation of minor actinides. In this article, the design policy of the pilot plant is elaborated for each design area: safety, subcriticality management, subcritical core, accelerator, target and in-vessel components. The conceptual design of the pilot ADS is also presented: 200 MW of thermal output, k_{eff} below 0.95, introduction of control rod, 1.0 GeV – 10mA accelerator and roughly-estimated size of in-vessel components.

KEYWORDS: pilot plant, ADS, lead -bismuth eutectic, subcriticality management

I. Introduction

To transmute minor actinides (MA), which is an issue as a heat generation and long-lived radioactive source in geological disposal, Japan Atomic Energy Agency (JAEA) has designed an 800 MW accelerator-driven system (ADS) and has been developing elemental technologies based on its design conditions.[1,2] This ADS consists of nitride fuel containing MA and plutonium (Pu) without uranium and has the capability to transmute 250 kg of MA per year.

Many novel technologies are used in the ADS, and basic research is being conducted at JAEA for each of them. As the next research and development, the construction and testing of engineering-scale facilities for each of the new technologies will be necessary. The facilities include the low-energy accelerator facility mentioned in Sec. IV.3, the proton irradiation facility in Sec. IV.4, and the in-vessel component test facility in Sec. IV.5. By integrating the results of development at the engineering-scale facilities, a pilot plant will be able to be constructed.

The pilot plant will address several remaining technical issues, subcriticality management, irradiation of MA fuel assemblies, and integrity of target material, for the construction of the 800 MW plant (full-scale ADS hereafter). In this article, after the description of the full-scale ADS in Sec. II, the design policy of the pilot plant will be elaborated for each of technical issues in Sec. IV.

II. Full-Scale ADS

First, we describe the specifications, timing, and scale of deployment of the full-scale ADS, which is the ultimate goal of the project. The full-scale ADS consists of a proton accelerator connected to a tank-type lead-bismuth-cooled fast reactor core. The power of the core is 800 MWt, and the maximum effective multiplication factor during operation is k_{eff} =0.98. The core does not have control rods, and the beam current of the accelerator is adjusted along with subcriticality change due to burnup to keep the power constant. The fuel pellet in the core is (MA+Pu)N+ZrN, which is uranium-free fuel to prevent the formation of Pu, since Pu competes with MA for transmutation by fission reaction. because Pu is competitor of MA in terms of transmutation through fission reaction. Nitrides are employed because of their high thermal conductivity and the good coexistence of MAN and PuN. ZrN is added to stabilize the fuel material and appropriately dilute the actinide density.

The proton energy is designed to be 1.5 GeV to generate a sufficiently large number of spallation neutrons per power of the proton beam and to keep the current value through the beam window, which is the boundary between the target and the accelerator, sufficiently small. The maximum current value is 15 mA to obtain 800 MWt from the subcritical core. The proton target is lead-bismuth liquid metal, which has a large mass number and can produce spallation neutrons in abundance. The liquid metal has the advantage that the heat generated by the proton beam can be efficiently removed and can be used also as MA fuel coolant.

The ADS is tank-type reactor inside which the target, MA core, and neutron shielding are arranged from the center. On the outside of the shielding, heat exchangers with pressurized water, circulation pumps, and fuel exchangers are arranged.

Figure 1 shows an example of deployment of partitioning and transmutation (P&T) technology including ADS in Japan. Currently, about 30 GWe of light water reactors (LWRs) exist, and it is planned to start transitioning to the fast breeder reactor (FBR) cycle during the 21th century. Reprocessing of LWR spent fuel is expected to start around 2026. In this example, the aim is to add MA separation capability to the reprocessing plant around 2050, to recover about one ton of MA per year. Since the annual MA transmutation capacity of a full-scale ADS is 250 kg, about four ADSs in Japan is operated after 2050 to transmute MA. Without P&T, 50000 vitrified wastes (150L) are expected to be generated, which

*Corresponding author, E-mail: nishihara.kenji@jaea.go.jp

will be reduced to 17000 with the introduction of P&T.[3)]

The operation of the pilot ADS will be started about 10 years before the full-scale ADS and will play a role in solving several technical issues that have not been proven for the full-scale ADS operation.

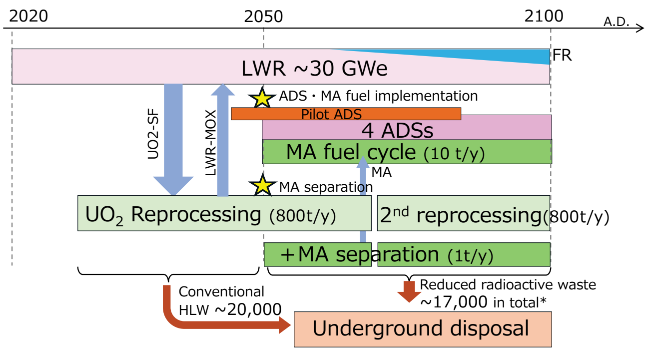


Fig. 1 Example of P&T deployment in Japanese LWR case

III. Calculation Method

The main characteristics of the full-scale and pilot ADS have been calculated by the ADS-3D code system[4)] which includes several codes for the analysis of proton current, reactivities, power distribution, depletion, etc. In ADS-3D, the proton and high-energy neutrons above 20 MeV are transported by the Monte Carlo method, the low-energy neutrons are calculated by the Sn method for both fixed-source and eigenvalue calculations with 73-group cross sections, and the composition change due to depletion is calculated by the matrix exponential and Bateman methods.

IV. Design Policy for Each Component

1. Safety and Subcriticality Management

For the safety design of ADS, the reference guideline can be found in the safety evaluation of lead-cooled fast reactors in the Generation IV International Forum (GIF).[5)] Lead-bismuth cooled reactor is considered within the scope of lead-cooled reactors. The major differences of ADS from critical reactors are that the accelerator is connected to the system and that it is operated in subcritical state. The proton beam duct is connected to the outside of the reactor, which could be a potential release path for radioactive materials. However, the pilot ADS would have multiple fast shutoff valves that could operate in multiples to prevent the release.

About the subcritical operation, due to insufficient experience in subcriticality management of the ADS, it is judged to be difficult to design a pilot ADS with near criticality and without control rods as the full-scale ADS, and a conservative design shall be adopted. In other words, the design policy for the subcriticality is that the pilot ADS will be operated at a deeper subcriticality than the full-scale ADS, and the reactor shutdown system by neutron absorption (control rod hereafter), which is omitted in the full-scale ADS, will be equipped. After the subcriticality control technology is matured in the pilot ADS, the full-scale ADS can be operated without control rods at shallow subcriticality.

Figure 2 shows the concept of subcriticality control for the fast reactor (Monju), full-scale ADS, and pilot ADS. Monju

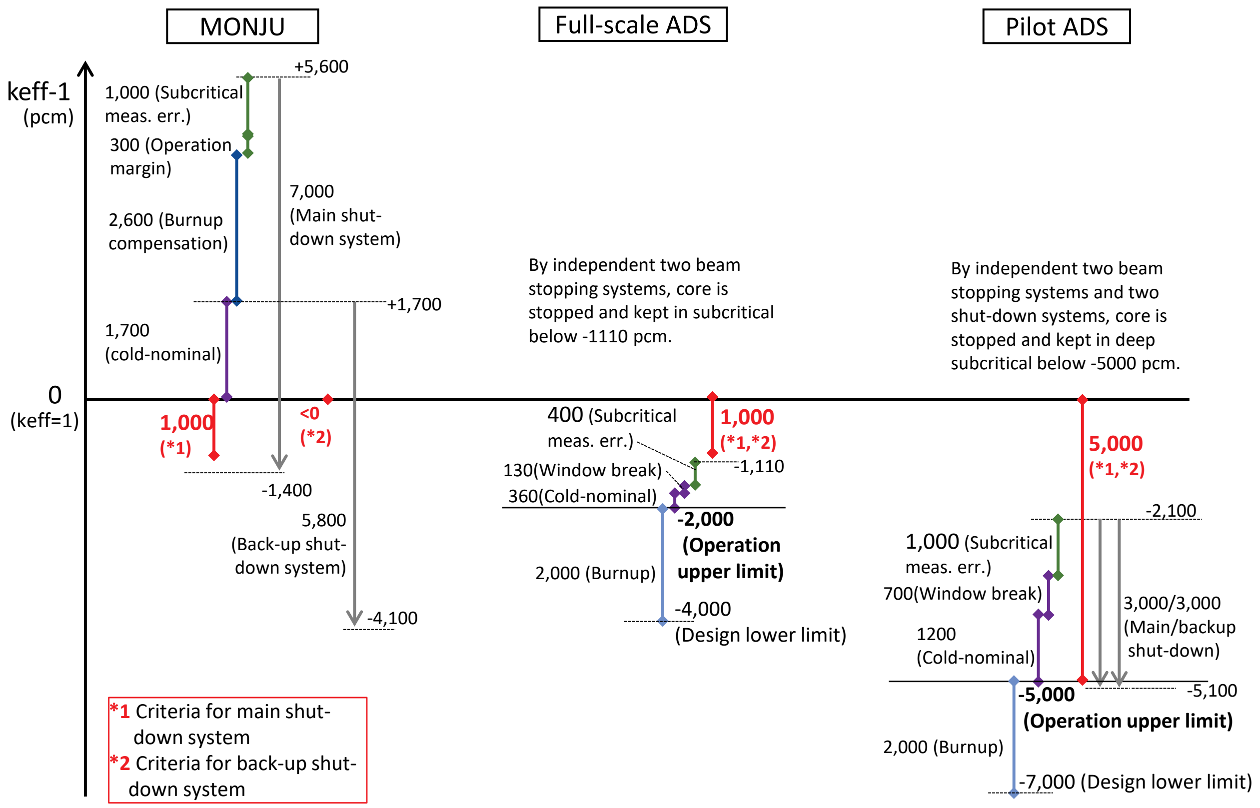


Fig. 2 Subcriticality management of fast reactor and ADS

was a Japanese experimental FBR with a thermal output of 714 MW. It is operated near criticality in nominal and transient operation. The main reactor shutdown system, which also serves as the operation system, is required to make the core in a subcritical cold shutdown state below -1000 pcm at any condition in consideration of various reactivities.[6] These reactivities are power defect (1900 pcm), burnup (2500 pcm), operating margin (300 pcm), and subcriticality measurement error (1000 pcm). Monju's main reactor shutdown system is designed to have a reactivity value of over 7100 pcm and the ability to go subcritical below -1400 pcm at any condition. On the other hand, the auxiliary shutdown system is required to be in a cold shutdown state of less than 0 pcm when the main shutdown system is stuck in the rated operation state. The design reactivity of the system is much higher (5900 pcm) than the requirement (1900 pcm).

This subcriticality management is applied to the full-scale ADS. The reactor shutdown system is required to make the core in cold shut down below -1000 pcm for all core conditions. In normal operation, the subcriticality of the ADS is designed to be below -2000 pcm. Considering the power defect (360 pcm), reactivity at beam window failure (130 pcm), and subcriticality measurement error (400 pcm), possible reactivity insertion is 890 pcm and subcriticality is always less than -1110 pcm. This means that the core is below -1000 pcm without any reactivity control. Therefore, the only role of the reactor shutdown system is to suspend the proton beam. After the proton beam is stopped, the core immediately reaches a subcritical low temperature state below -1110 pcm. Since the methods of stopping the beam can be easily multiplexed and diversified, such as proton beam ion source shutdown, multiple beam shutters and release of magnetic field of the bending magnet, these can be used as the main and auxiliary reactor shutdown systems.

Here, the breakage of the beam window does not necessarily need to be taken into account because it will be categorized to the accidental situation to be avoided, but since the beam window is used in a harsh environment, it may be difficult to make the probability of breakage very small, so it was included conservatively. The safety requirement relevant to the window breakage have to be investigated more in the next design step.

The subcriticality measurement error of 400 pcm is tentative value for the design of full-scale ADS. As mentioned earlier, this value should be confirmed by the pilot ADS due to lack of sufficient experience of ADS operation.

Finally, in the pilot ADS the subcriticality that should be reached in cold shutdown state is supposed to be extremely large (-5000 pcm), considering that this is the first high power ADS using lead-bismuth as the coolant. This value corresponds to the standard value of subcriticality that does not require subcriticality control in Japanese regulations (k_{eff} =0.95).

In the pilot ADS, the reactivity by power defect (1200 pcm), beam window failure (700 pcm) and conservatively supposed measurement error (1000 pcm) are larger than those in the full-scale ADS because of the smaller core size and poor experience of reactivity measurement. Therefore, if the subcriticality during operation is determined based on the identical concept to the full-scale ADS, the system must be operated at impractically deep subcriticality. To avoid this, two systems of neutron absorbers (control rods) are introduced as reactor shutdown systems in the pilot ADS, and a cold shutdown state below -5000 pcm is achieved by the same concept as in the critical fast reactor. Assuming a conservative subcriticality measurement error of 1000 pcm, the required control rod reactivity value is more than 2900 pcm. Here, the reactivity of the control rods is set at 3000 pcm. To achieve cold shutdown, two or more proton beam shutdown mechanisms are also provided as reactor shutdown systems.

The subcriticality range of the pilot ADS in operation is less than -5000 pcm, which causes 1/2.5 times smaller multiplication than the full-scale ADS. The power of the subcritical core is set to be 1/4 of the full-scale ADS, i.e., 200 MW, because it is technically feasible to use a smaller accelerator and target power than the full-scale ADS as well. Since the transmutation performance of MA is proportional to the thermal power, the maximum transmutation performance is also 1/4 (60 kg/year) of the full-scale ADS whose transmutation rate is 250 kg/year[4]. This performance is modest comparing to the full-scale ADS, but it still usable for the practical transmutation of MA.

2. Subcritical Core

As described in the previous section, the core power of the pilot ADS is 200 MW, and the core is smaller than that of the full-scale ADS. However, the assembly design will have the same dimensions and materials for technical continuity to the full-scale ADS, and only the fuel inside the clad will be changed from MAN to mixed oxide (MOX).

Although nitride MA fuel will be used in the full-scale ADS, only a few small-scale irradiation tests of fuel pins have been conducted so far, and there is a lack of irradiation facilities internationally. Therefore, as the design policy for the fuel material in the subcritical core, the first-loading fuel of the pilot ADS is decided to be MOX fuel, for which many experiences has been accumulated in experimental fast reactors. Then, toward the realization of the full-scale ADS, the pilot ADS will serve an irradiation function for MA nitride fuels, and the loading of MA nitride fuels will be increased step by step to eventually achieve full-core loading for the MA transmutation.

The uncertainty of the nuclear data of MA with respect to criticality and reactivities, such as void and temperature effects, is also an issue to be resolved. The gradual loading of MA into the pilot ADS and validation by the reactor physics experiments will resolve this issue.

We consider two phases for the pilot ADS core as shown in **Table 1**. In the initial phase, the design has many fuel assemblies with small power density. In the second phase, the number of assemblies is reduced to achieve a higher power density, which is equivalent to that of the full-scale ADS, and irradiation tests and partial- and full-loading of the MA fuel assemblies are conducted.

Pu enrichment, which is defined as the volume ratio to whole actinide oxide, is 23% and 26%, respectively. Other actinide of the pilot ADS is uranium oxide, while that of the full-scale ADS is MA nitride. Operation duration of the pilot ADS is much shorter than the full-scale ADS, because k_{eff} drops faster. MA behaves as better fertile than ^{238}U in respect to criticality.

Table 1 ADS core design

	Pilot ADS 1st phase	Pilot ADS 2nd phase	Full-scale ADS[7]
Thermal output (MW)	200	200	800
Number of assemblies	90	63	276
Peak power density(W/cm^3)	240	320	320
Pu enrichment (vol%)	23	26	37
Operation duration (day)	90	90	300
k_{eff} (BOC/EOC)	0.95/0.94	0.95/0.93	0.98/0.96
Beam energy (GeV)	1.0	1.0	1.5
Current (mA, BOC/EOC)	7/9	7/10	9/15
Beam power (MW)	7/9	7/10	13.5/22.5

3. Accelerator

Since the pilot ADS devotes to develop the full-scale ADS, its accelerator must have the same technical characteristics and performance as the full-scale ADS. The accelerator will have the stepwise current adjustment required for startup and shutdown of the ADS and will equip the fault tolerance function. The fault tolerance function is used to prevent the accelerator from shutting down due to equipment failure to achieve high operational efficiency. The function includes duplication of low-energy part of the accelerator keeping one of two under hot-standby. For the high energy part, in a case of some of the superconducting radio frequency (SRF) cavities fail, the nearby non-faulty element compensates for the faulty element. [8]

As mentioned at the end of Section IV.1, the core power of the pilot ADS was set at 200 MW. To achieve this output, around 10 megawatts of beam power (MWb) is required. Therefore, the design policy for the accelerator is 10 MWb of power, power adjustment and fault compensation.

In the pilot ADS, the proton energy and current are set to 1.0 GeV and 10 mA among several possible combinations of energy and current such as 0.6 GeV and 17mA, or 1.5GeV and 7 mA, because in the energy region above 1.0 GeV there is no significant change in the required acceleration technique and the number of spallation neutrons produced per proton power. The lower energy of 1.0 GeV is advantageous in the accelerator construction cost. Instead, the low proton energy causes the higher current by which heat and damage to the beam window increases. However, the current of 10 mA is still smaller than that of the full-scale ADS (15 mA) and appropriate step towards the full-scale.

The performance of the normal-conducting proton linear accelerator currently in operation at Japan Proton Accelerator Complex (J-PARC) is 0.4 GeV and 0.33 mA, requiring a threefold increase in energy and a 30-fold increase in current. Since high current, current adjustment function, and fault tolerance in the low-energy acceleration are considered to be major issues, it is reasonable to first construct and test the low-energy portion of the pilot ADS (about 20 MeV, 10 mA). **Figure 3** shows the accelerator elements for each acceleration energy and the energies to be aimed for at each stage.[9]

4. Target

The target concept and dimensions of the pilot ADS are identical to those of the full-scale ADS.[10] That is, a beam duct with a vacuum inside is inserted into the center of the reactor, and protons are passed through thin boundary of the steal, then generates neutrons in a lead-bismuth liquid alloy target.

The boundary through which the protons pass is called the beam window, and the issues of this material are resistance to irradiation, corrosion, and external pressure at high temperatures for one or two years of operation. In the design policy of the target, material and shape of the beam window is identical to those of the full-scale ADS, while the irradiation period is much shorter than one year. Then, the period is extended gradually to more than one year.

In the international joint project MEGAPIE, material integrity was confirmed at low temperature (350°C), low irradiation dose (7 DPA), and under lead-bismuth flow.[11] In contrast, the full-scale ADS will be used under high temperature (500°C), high irradiation dose (100 DPA), and lead-bismuth flow. Since there is currently no experimental facility in Japan or overseas that can simulate the environment of the full-scale ADS, we are planning to establish the proton

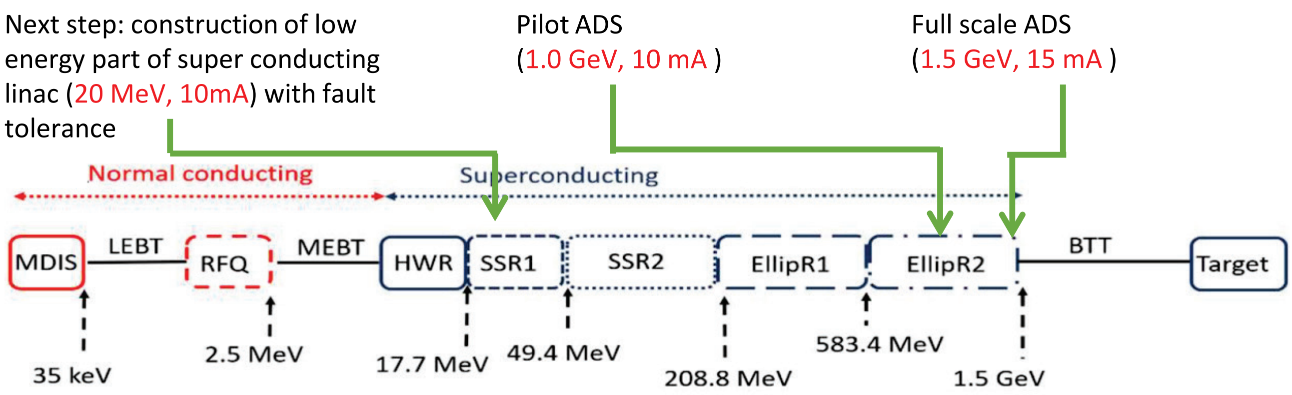


Fig. 3 Superconducting linac for ADS

irradiation facility at J-PARC that can simulate high temperature (500°C), medium irradiation (20 DPA), and lead-bismuth flow.[12] Based on the achievement of research and development in this facility, the pilot ADS will be initially designed for high temperature (500°C) and medium irradiation (20 DPA). Then, duration of the beam window irradiation will be gradually extended from 90 days to achieve high irradiation (100 DPA), which will lead to the full-scale ADS.

5. In-Vessel Component

Finally, the design policy for the in-vessel component of the pilot ADS is to apply the same kind as for the full-scale ADS,[13] although the corresponding power is 1/4. That is, the pumps are mechanical pumps, and the secondary system of the heat exchanger is pressurized water as well as the full-scale ADS. The secondary system and beyond have not yet been studied, but if economically rational in terms of supplying power to accelerator of the pilot ADS, a power generation turbine will be equipped. The capacity of the heat exchanger and pumps is determined in proportion to the reactor power. Since the power output of the pilot ADS is designed to be 1/4 of the full-scale ADS, the cross-sectional area can be reduced to 1/4 with the same height of the components. As illustrated in **Fig. 4**, the core, in-vessel structure, and reactor vessel are reduced compared to the full-scale ADS. Although the pilot ADS has control rods and drive mechanism for them, their design has not performed yet and are not illustrated in the figure.

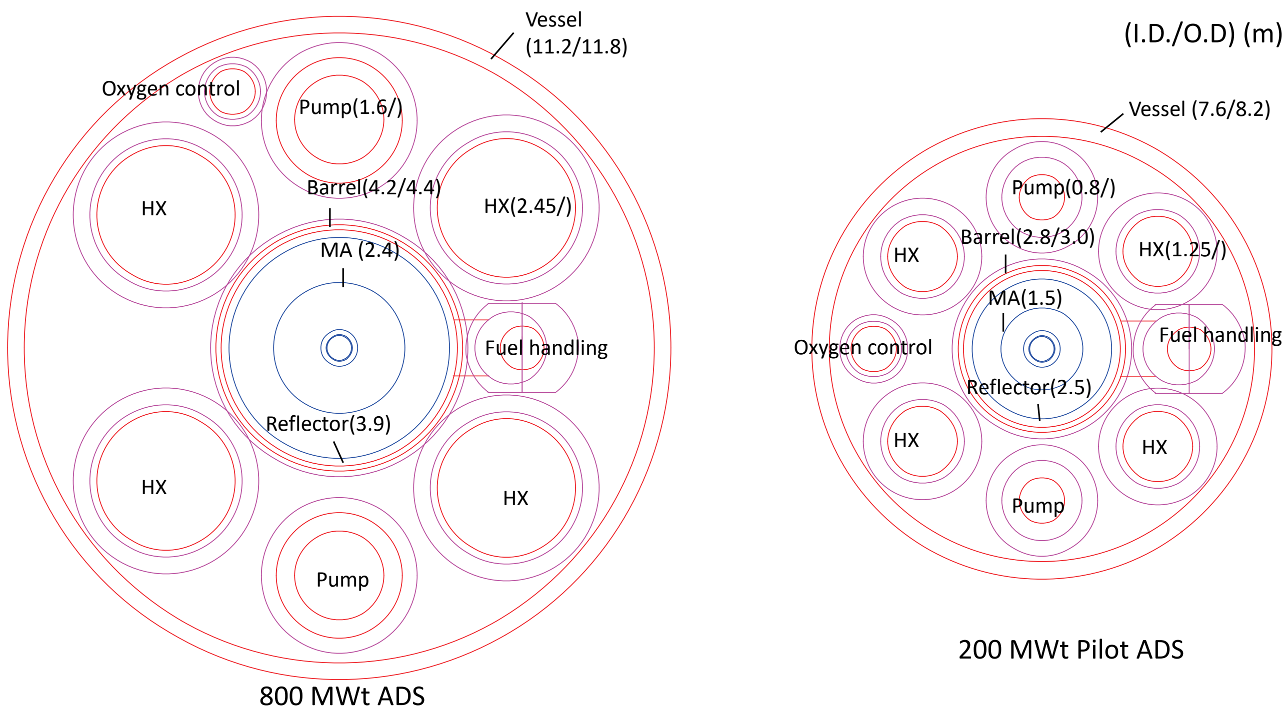
Since there has been no experience in manufacturing and testing such large equipment for lead-bismuth in Japan, a non-radioactive (cold), in-vessel component test facility where pump, heat exchanger, etc. will be fabricated and tested in practical scale is required prior to detailed design and permitting of the pilot ADS.

V. Conclusion

JAEA has performed basic research and investigated engineering-scale facilities such as a proton irradiation facility in J-PARC as the next step of development for ADS. The pilot ADS proposed in this article will be constructed based on these engineering-scale facilities and will address several remaining technical issues for the construction of the 800 MW plant (full-scale ADS). These issues are subcriticality management, irradiation of MA fuel assemblies and integrity of target material.

In this article, the design policy of the pilot ADS was elaborated for each design area: safety, subcriticality management, subcritical core, accelerator, target and in-vessel components. At the same time, the conceptual design of the pilot ADS was presented as 200 MW of thermal output, k_{eff} below 0.95, introduction of control rod, 1.0 GeV – 10mA accelerator and roughly-estimated size of in-vessel components.

The necessary test facilities to reach the pilot ADS are J-PARC proton irradiation facility, in-vessel component test facility and low-energy accelerator test plant. Their corresponding technical levels are shown in **Fig. 5** with necessary facilities for MA fuel cycle technology (partitioning and MA fuel processing). JAEA will continue efforts to increase the readiness level in this way.



Fig, 4 Cross sectional view of in-vessel equipment

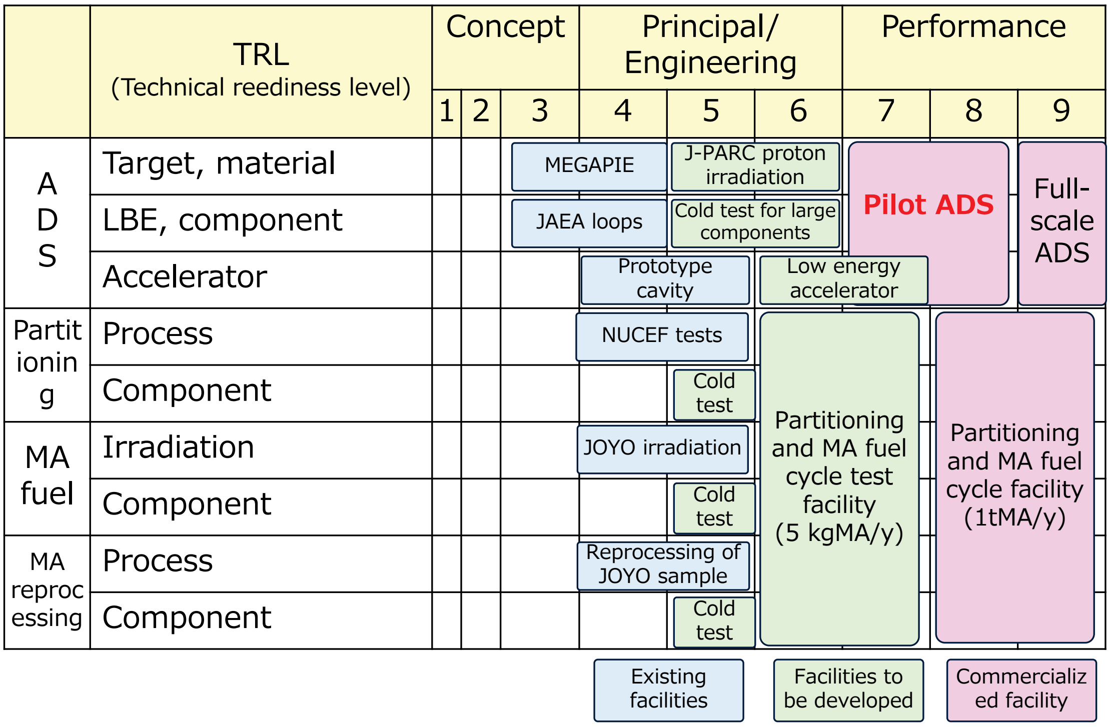


Fig. 5 Technical readiness level and corresponding facilities

References

1) T. Sugawara, et al, "Research and development activities for accelerator-driven system in JAEA," *Prog. Nucl. Energy*, **106**, 27-33 (2018).
2) Present status of R&D in JAEA on partitioning and transmutation technology, JAEA-Review 2022-052 (2023), [in Japanese].
3) K. Nishihara, et. al," Impact of partitioning and transmutation on LWR high-level waste disposal," *J. Nucl. Sci. Technol.*, **45**[1], 84-97 (2008).
4) T. Sugawara, et. al, "Development of three-dimensional reactor analysis code system for accelerator-driven system, ADS3D and its application with subcriticality adjustment mechanism," *J. Nucl. Sci. Technol.*, **53**[12], 2018-2027 (2016).
5) GIF LFR provisional System Steering Committee, Lead-cooled Fast Reactor (LFR) System Safety Assessment (2020).
6) Application for Establishment Permit of Fast Breeder Reactor Research and Development Center (Prototype Fast Breeder Reactor Monju), Power Reactor and Nuclear Fuel Development Corporation (1980), [in Japanese].
7) T. Sugawara, R. Katano, K. Tsujimoto, "Impact of impurity in transmutation cycle on neutronics design of revised accelerator-driven system," *Ann. Nucl. Energy*, **111**, 449-459 (2018).
8) B. Y. Rendon, et. al, "Design and beam dynamic studies of a 30-MW superconducting linac for an accelerator-driven subcritical system," *Phys. Rev. Accel. Beams* **24**, 120101 (2021).
9) B. Y. Rendon, et. al, "Design and beam dynamic studies of a 30-MW superconducting linac for an accelerator-driven subcritical system," *Phys. Rev. Accel. Beams* **24**, 120101 (2021).
10) T. Sugawara, et. al, "Design study of beam window for accelerator-driven system with subcriticality adjustment rod," *Proceedings of 26th International Conference on Nuclear Engineering (ICONE-26)* (Internet), 10 Pages, (2018).
11) S. Saito, et. al, "Experimental validation of tensile properties measured with thick samples taken from MEGAPIE target," *Journal of Nuclear Materials*, **534**, 152146 (2020).
12) F. Maekawa, "A Plan of Proton Irradiation Facility at J-PARC and possibilities of application to nuclear data research," *Proceedings of the 2021 Symposium on Nuclear Data*, Nov. 18-19, 2021, JAEA-Conf 2022-001 (2022).
13) H. Akimoto and T. Sugawara, Thermal Design Study of Lead-bismuth Cooled Accelerator Driven System: (1) Study on Thermal Hydraulic Behavior under Normal Operation Condition, JAEA-Data/Code 2016-008 (2016), [in Japanese].