Phase II Final Report of Feasibility Study on Commercialized Fast Reactor Cycle Systems

Executive Summary

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The Japan Atomic Power Company

The “Feasibility Study on Commercialized Fast Reactor (FR) Cycle Systems” (hereinafter, “Feasibility Study”) was initiated in July, 1999 with an initial two-year period of study (Phase I), and followed by a five-year period of study (Phase II) that was initiated in 2001. The Phase II final report was recently compiled, and the outline of the Phase II study is as follows:

1. Progress of the Feasibility Study

Taking into consideration the recommendations on Dec., 1997 by the “Round-Table Conference on Fast Breeder Reactor (FBR)” of the Atomic Energy Commission of Japan and other discussion results, the Japan Atomic Energy Agency (JAEA) and electric utilities initiated the Feasibility Study in July, 1999 in collaboration with the Central Research Institute of Electric Power Industry (CRIEPI) and manufacturers, in order to effectively utilize the accumulated knowledge from the demonstration fast breeder reactor (DFBR) design, as well as the construction/operation experience from an experimental FR, JOYO and a prototype FBR, MONJU. The objective of this study is “to present both an appropriate picture of commercialization of the FR cycle and the research and development (R&D) programs leading up to the commercialization in approximately 2015.”

A wide range of technical options have been evaluated to select several promising concepts as candidates for the commercialization in the Phase I study from July 1999 to the Japanese fiscal year (JFY) 2000. The Phase II study was initiated in JFY2001, aiming “to identify the most promising candidate concept for the commercialization of the FR cycle, as well as to draw up the future R&D program”. Based on recent progress, it was required by the “Framework for Nuclear Energy Policy” issued in 2005 to present “a principle for prioritizing R&D as well as R&D programs until approximately 2015, and the potential future issues” as the outcomes of the Phase II study.

In this study, evaluation of conceptual design features was performed in order to select promising FR systems and fuel cycle systems that can meet the design requirements (listed in Table 1), established by specifying the five development goals [i) safety; ii) economic competitiveness; iii) reduction of environmental burden; iv) efficient utilization of nuclear fuel resources; and v) enhancement of nuclear non-proliferation].

2. Principle for investigation and prioritization of promising candidate concepts

In creating the concepts of the FR system and the fuel cycle system, efforts were made to set up design concepts that can demonstrate the best possible performance of each of the system concepts, by positively employing new materials and innovative technologies to improve economic and other performance. These design concepts were evaluated technically from two perspectives, [i) potential conformity to the five development goals, ii) the pro tem technical feasibility of new materials and innovative technologies by considering possible international cooperation], to discuss principles for the selection and prioritization of promising candidate concepts.

In addition, some of the adopted new materials and innovative technologies have a high level of technical difficulty; however, it was assumed that even such materials and technologies should be applicable, as expected in this study. Therefore, it is necessary to form a clearer view of the feasibility by conducting elemental experiments and research on each of the materials and technologies.

2.1 Technical summary of FR systems

2.1.1 Sodium-cooled reactor (Figure 1)

To improve economy, new materials, including ODS (Oxide Dispersion Strengthened) steel cladding and high-chromium steel, as well as innovative technologies such as the compact reactor vessel, the integrated intermediate heat exchanger with primary pump and a reduction in the number of heat transport loops (two loops for a 1.5GWe plant) were adopted. In addition, an increase in the capacity of each component was employed to establish drastically-compacted plant system concepts compared with the conventional concepts, and, thereby, greatly reduce the amount of plant materials and its building volume.

Reduction in the fuel costs by increasing the core fuel burnup (150GWd/t; core-averaged value) and in the operating costs by extending the operation period (18-26 months) resulted in the possibility of achieving the goals of power generating costs. A high level of potential conformity to design requirements including the reduction of environmental burden and the efficient utilization of nuclear fuel resources was confirmed in the case of mixed oxide (MOX) fuel.

Furthermore, additional improvements were made from the perspective of enhancing safety and reliability by the addition of a passive shutdown function, the assurance of core cooling function by natural circulation, the application of double-walled heat transfer tube for the steam generator, and the complete adoption of a double-walled piping geometry.

On the other hand, as sodium is opaque and chemically active, it is necessary to pay great attention to both maintainability and repairability from the design stage to assure plant reliability. For this reason, maintenance and repair guidelines that would be needed for a commercial FR were discussed by considering the advantages of sodium including good compatibility with structural materials, with reference to efforts and trends of maintainability and repairability for light water reactors (LWRs).

Design studies were performed so as to conform to the maintenance and repair guidelines, and development of required inspection equipment was initiated. It is still necessary to continue the development of inspection and repair technologies; however, when considering the experiences of developing inspection devices at MONJU and the DFBR study as well as the testing results of inspection equipment obtained in the Phase II study, in addition to the actual results of operation and maintenance at JOYO, it is considered possible to assure maintainability and repairability equivalent to those of LWRs in the future.

Issues seriously affecting technical feasibility are mainly limited to the technical development required to achieve the economic goal. However, innovative technologies having a high level of technical difficulty could be replaced by alternative technologies, which are extensions of existing technologies and achieved with less significant development risk, though with a degradation in economy. Accordingly, when considering the development performance including that of MONJU and DFBR, it is possible to anticipate technical feasibility with a higher degree of reliability than other concepts.

In addition, the sodium-cooled reactor was selected as one of the candidate reactor types in the Generation IV International Forum (GIF) project that is actively promoted in multilateral cooperation, and the sodium-cooled reactor design concept in this Phase II study has become a representative candidate concept of such a reactor type within the GIF project. Therefore, it is possible that the sodium-cooled reactor design concept in this study may be developed as an international standard, and, furthermore, it is expected that technical feasibility can be enhanced by an international sharing of the research tasks to be addressed for the realization.

Moreover, applying metallic fuel for sodium-cooled reactors makes possible the design of a core with a higher breeding ratio with less Pu inventory, in addition to an improvement of the economy through increased average fuel burnup including blanket fuel. For example, maintaining the equivalent fuel burnup of the future LWR(55GWd/t), a metallic fuelled core can assure a breeding ratio of ~1.26 compared with ~1.20 of a MOX fuelled core, as well as less fuel inventory than the MOX core by 11%. From these results, it is expected that the sodium-cooled reactor can cope flexibly with the possible tight supply-demand situation for uranium resources in the future which might be caused by a more accelerated introduction of FR or an increased nuclear power generation capacity than is presently anticipated.

2.1.2 Helium gas-cooled reactor

The helium gas-cooled reactor has the potential of meeting all the design requirements through the application of nitride fuel; however, its fuel cycle cost is increased due to the lower fuel burnup than that of the sodium-cooled reactor. On the other hand, since it allows a high reactor outlet temperature of approximately 850℃, it is attractive as a high temperature heat source that can not be realized with the sodium-cooled reactor.

Concerning the technical feasibility, the development of coated particle nitride fuel should be an essential technical consideration that will determine the conceptual applicability. Specific issues include the development of coating material for particle fuel as well as a block-typed fuel subassembly that has high temperature resistance, which would require fundamental R&D and are not likely to be replaced by alternative technology at this stage. On the other hand, since the helium gas-cooled reactor was selected as one of the candidate reactor types at the GIF project, it may be possible to break through these fundamental issues in international cooperation.

2.1.3 Lead-bismuth-cooled reactor

By applying nitride fuel, the lead-bismuth-cooled reactor has the potential to achieve core performance equivalent to the sodium-cooled reactor and meet all the design requirements. Concerning technical feasibility, essential issues include the corrosion of steel such as the fuel cladding in addition to the development of the nitride fuel. Accordingly, fundamental R&D is needed to develop corrosion prevention technology and corrosion resistant material, which will determine the conceptual applicability. It is quite difficult to prepare alternative technologies for these issues at this stage.

Although the lead-bismuth-cooled reactor was also selected as one of the candidate reactor types at the GIF project, no country has taken leadership in its development thus far, and, hence, a breakthrough in the fundamental issues by international cooperation is unlikely.

2.1.4 Water-cooled reactor

As for the efficient utilization of nuclear fuel resources in the design requirements, the lower breeding ratio and larger fuel inventory of the water-cooled reactor require more time for the transition into the FR era and consequently reduce the introduction effect as FR from the viewpoint of saving natural uranium resources. In addition, the water-cooled reactor has lower performance in accepting and burning minor actinides (MAs) that are recovered by the reprocessing of spent LWR fuel, compared with other reactor concepts. It has the potential of meeting the other design requirements such as safety, economy, and nuclear proliferation resistance.

In order to anticipate the technical feasibility, the water-cooled reactor has difficulties, which are, however, limited to the core fuel related issues. It is necessary to develop cladding material and to discuss countermeasures for the mitigation of the consequences of core damage. In addition, since boiling water reactor (BWR)-typed FR, which was discussed in this study, was not selected as a candidate reactor type at the GIF project, international cooperation is limited to basic research topics at this time.

2.1.5 Promising concepts for the FR system

Promising concepts for the FR system have been identified based on the technical summary results of candidate concepts for the FR system as shown in Table 2. The sodium-cooled reactor is superior to other reactor types from the perspective of both potential conformity to the design requirements and technical feasibility. Furthermore, since it has the potential to be adopted as an international standard concept, which may help to enhance technical feasibility, it is evaluated as the most promising FR system concept.

The helium gas-cooled reactor has the potential to meet all the design requirements, and also has the potential to accommodate the various needs as a high temperature heat source, which makes the helium gas-cooled reactor different from all other reactor types. Although it has fundamental problems that will determine conceptual applicability, several countries, including the USA and France, have shown eagerness for its development, and there is a good possibility of solving difficulties through international cooperation.

The other FR concepts cannot become superior to the above-mentioned promising ones from the perspective of either the potential conformity to design requirements or technical feasibility.

2.2 Technical summary of fuel cycle systems

2.2.1 Combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system (Figure 2)

The advanced aqueous system can eliminate “the purification process of U product and Pu product,” which is one of the main processes in the conventional technology (PUREX process), because a certain amount of fission products (FPs) in recycled fuel (low decontamination) can be accepted into the FR cycle. In addition, the introduction of crystallization technology, which will recover approximately 70% of the uranium dominating (approximately 80%) the heavy metal (HM) mass in the solution of spent fuel beforehand, allows a drastic reduction in the throughput in the following processes, leading to a streamlining of installations.

The powder mixing process dominating a large part of the conventional pelletizing process can be eliminated by making it possible to control Pu content through the mixture of U and Pu in the nitric acid solution stage. An integrated layout of a reprocessing system and a fuel fabrication system also results in a rational facility design. On the other hand, when compared with the conventional concepts, this concept has cost increase factors, including the addition of the MA recovery process in the reprocessing system as well as the necessity of a hot cell in the fuel fabrication system where the low decontaminated fuel can be handled.

As described above, this concept has both advantageous and disadvantageous impacts on economy; however, the advanced aqueous reprocessing system can greatly affect streamlining, such as almost halving the construction costs compared with the conventional technology through process elimination and the streamlining of installations that are realized by the lowered decontamination. Accordingly, there is a possibility of meeting the design requirement on economy. The possibility of meeting the design requirements, including efficient utilization of nuclear fuel resources, reduction of environmental burden and enhancement of nuclear non-proliferation is evident as well.

The advanced aqueous reprocessing system requires the development of processes and components for new technologies such as the crystallization and the MA recovery; however, since abundant technical knowledge obtained through experiences at the Tokai Reprocessing Plant in JAEA and at the Rokkasho reprocessing plant in the Japan Nuclear Fuel Limited can be utilized, it is possible to anticipate the technical feasibility with a high degree of reliability. Furthermore, as the advanced aqueous reprocessing system is the focus of development in France, enhancement of the technical feasibility is expected through international cooperation.

It becomes necessary to develop components with consideration given to remote maintainability and repairability to address the fuel fabrication in a hot cell; however, as basic processes of the simplified pelletizing fuel fabrication system are common to those of the conventional processes, it is possible to anticipate the feasibility with a high degree of reliability.

Besides, the fundamental research of the supercritical direct extraction process, which can simultaneously perform both the dissolution of spent fuel and the extraction of U and Pu, continues, because it has the potential to further simplify the system configuration, and to allow better streamlining in aspects of economy and the amount of waste generation of the advanced aqueous reprocessing.

2.2.2 Combination of the metal electrorefining reprocessing system and the injection casting fuel fabrication system

Fuel reprocessing by the metal electrorefining recovers U and TRU from spent metallic fuel using the principle of the electrolytic refining, and fuel fabrication by the injection casting process casts fuel by melting the recovered U and TRU, and both systems allow more simplified processes compared with the other fuel cycle systems. It has been confirmed through the results of previous investigations that the combination system creates the potential of meeting all the design requirements. Especially in the case of a small-scale cycle facility, it is anticipated to have better potential conformity to the economy requirement than the other systems. However, it is anticipated that the economy of a large-scale facility will be inferior to that of the “combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system” because the batch process mode of both the reprocessing and fuel fabrication systems can not obtain a good scale factor.

Moreover, the volume of high-level radioactive solidified waste (HLW) per unit electricity output becomes larger than the other fuel cycle system concepts because of the limited amount of FPs that can be mixed in HLW, which is generated through the metal electrorefining reprocessing and processed into glass-bonded sodalite (the raw material is zeolite).

Since it is considered that the applicability of the main processes has almost been confirmed when considering the development performance in the USA, it is possible to anticipate technical feasibility.

The remaining considerations include confirmation of process applicability by using spent fuel, the reduction in the amount of HLW, and the development of components with consideration given to remote maintainability and repairability. Although the technical difficulties of those considerations are not high, development is anticipated to take a considerable amount of time because domestic infrastructure for the development is insufficient. For this reason, international cooperation with the USA, a country that has development performance, and other countries, should be important.

2.2.3 Combination of the advanced aqueous reprocessing system and the vibration packing fuel fabrication system

When the vibration packing fuel fabrication system is coupled with the advanced aqueous reprocessing system, spherical fuel particles are manufactured by the “gelation process”, which produces good results in the manufacture of fuel of the high-temperature gas-cooled reactor (HTTR, etc.), and packed in cladding. Accordingly, it can eliminate the powder mixing process which dominates a large part of the conventional pelletizing fuel fabrication system. Furthermore, it has additional advantages such as fine powder not being generated and better suitability for remote maintainability and repairability compared with the simplified pelletizing fuel fabrication system.

Achieving superior economy was once expected through the utilization of these advantages; however, inferior economy to the simplified pelletizing fuel fabrication system has been anticipated because it becomes essential to be equipped with large and small particle manufacturing lines in order to realize the packing density of fuel. Although the vibration packing fuel fabrication system has the potential of meeting all the design requirements, a system superior to the simplified pelletizing fuel fabrication system is unlikely.

Concerns include the development of components with consideration given to remote maintainability and repairability, and the inspection technique for axial distribution of the packing density of fuel. Less technical knowledge has been obtained compared with the simplified pelletizing fuel fabrication system; however, since the applicability of the system was confirmed by the manufacture performance of MA-bearing fuel, feasibility can be anticipated.

Concerning the “nitride coated particle fuel” that is compatible with the helium gas-cooled reactor, the addition of appropriate processes, including decladding, nitriding and coating, makes it possible to apply the advanced aqueous reprocessing as well as the “gelation process”(a part of the vibration packing fuel fabrication system) for manufacturing fuel. In this manner, a fuel cycle system suitable for the nitride coated particle fuel has a number of technical features in common with the “combination of the advanced aqueous reprocessing system and the vibration packing fuel fabrication system”, and, consequently, it is efficient to initiate the technology development on the basis of progress in FR system development such as the development of the nitride fuel subassembly.

Problems concerning the nitride coated particle fuel include decladding technology in reprocessing and coating technology in manufacturing fuel, as well as the development of the above-mentioned coating material and the fuel subassembly. In addition, for the nitride fuel, it is necessary to enrich (targeting on 99.9%) and apply ^{15}N, which has less natural abundance (0.37%), in order to suppress the generation of ^{14}C, which has a long half-life, in the fuel. For this reason, it will become necessary to develop a less expensive ^{15}N enrichment technology, as well as a ^{15}N recycling technology.

2.2.4 Combination of the oxide electrowinning reprocessing system and the vibration packing fuel fabrication system

Fuel reprocessing by the oxide electrowinnig recovers UO_2 and MOX from spent MOX fuel using the principle of electrolysis, and fuel fabrication by the vibration packing process packs fuel granules, that are obtained by crashing the fuel recovered on the cathodes, in the cladding, and the combination of the two allows a simple system, as well as cases applying the metal electrorefining system.

Investigations show the potential of its meeting all the design requirements including economy. However, the MOX and MA recovery technologies are still undergoing a verification of principles, and there remain a number of technical issues, such as countermeasures against material corrosion arising from the application of chlorine gas and oxygen gas, development of remote maintainability and repairability, and quality control of the fuel granules. Therefore, technical feasibility is inferior to the other concepts. Moreover, since it would require a domestic development infrastructure, development is anticipated to take a considerable amount of time.

2.2.5 Promising concepts for the fuel cycle system

Promising concepts for the fuel cycle system have been identified based on the technical summary results of candidate concepts for the fuel cycle system (Table 3). “Combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system,” which can cope with either MOX or nitride fuel, has potential conformity to the design requirements, as well as a high level of technical feasibility because it can be developed with an extension of the existing technologies. In addition, since it is expected to be developed through international cooperation, it is evaluated as the most promising fuel cycle system concept.

“Combination of the metal electrorefining reprocessing system and the injection casting fuel fabrication system” applied to metallic fuel that can improve core performance has the potential of meeting design requirements and is likely to have better small-scale cycle facility economy than the other concepts, in particular. Concerning technical feasibility, long-term development may be required; however, since international cooperation with the USA and other countries can be expected, it is suggested to be a promising fuel cycle concept.

The other fuel cycle concepts cannot achieve superiority over the above-mentioned promising concepts from the perspective of either potential conformity to the design requirements or technical feasibility.

2.3 Discussion on the principle for prioritization

2.3.1 Evaluation of the entire FR cycle system

In selecting promising FR cycle concepts, it is appropriate to evaluate potential conformity to the development goals, technical feasibility and other factors of not only the FR system and the fuel cycle system, respectively, but also the entire FR cycle system that is the combination of the two systems.

In the above-mentioned technical summary, it is concluded, for the FR system, that the “sodium-cooled reactor” is the most promising concept and the “helium gas-cooled reactor” is a promising concept. On the other hand, it is concluded, for the fuel cycle system, that the “combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system” is the most promising concept and the “combination of the metal electrorefining reprocessing system and the injection casting fuel fabrication system” is a promising concept.

In the evaluation of the FR cycle, promising FR cycle concepts have been established based on the technical summary results on respective FR and fuel cycle systems. The established concepts are described in the following:

(1) “Combination system of the sodium-cooled reactor, advanced aqueous reprocessing and simplified pelletizing fuel fabrication” (MOX fuel)

As this concept has the greatest potential conformity to the development goals, including economy (power generating costs), and as it is possible to anticipate its technical feasibility, it can be judged the most superior concept.

(2) “Combination system of the sodium-cooled reactor, metal electrorefining reprocessing and injection casting fuel fabrication” (metallic fuel)

This concept is not considered to be superior to the concept (a) in the comprehensive evaluation concerning the potential conformity to the development goals and technical feasibility; however, since it can improve the core performance by employing metallic fuel, it can be judged as being more attractive in terms of flexibly coping with possible future situations, such as tighter supply-demand for uranium resources than presently expected.

(3) “Combination system of the helium gas-cooled reactor, advanced aqueous reprocessing and coated particle fuel fabrication” (nitride fuel)

This concept is not considered to be superior to the concept (a) in the comprehensive evaluation concerning the potential conformity to the development goals and technical feasibility; however, since it can realize high reactor outlet temperature, it can be judged as being more attractive than (a) in terms of accommodating the various needs as a high temperature heat source.

2.3.2 Principle for prioritization

In order to prioritize R&D, the above-mentioned concept (a) is selected as “the concept to be developed with a focus on (principal concept)” because it is judged to be the most comprehensively superior concept by the technical summary. In addition, it is decided to designate those concepts having more attractiveness than the principal concept as “concepts to be developed in a complementary manner (complementary concept)” from the perspective of assuring diverse alternatives to uncertainties, including future needs, and the above-mentioned concepts (b) and (c) are selected as the complementary concepts.

In the future, the main R&D investment should be focused on the principal concept in consideration of efficient utilization of the limited research resources. In parallel, concerning the complementary concepts, R&D should be conducted with a focus on concerns that are judged as essential for technical feasibility and other aspects.

3. R&D Strategy in Phase III and beyond

3.1 R&D Prospects until approximately 2015 (Figure 3)

In the Phase II study, selection of promising candidate concepts for commercialization, establishment of the principle for prioritizing R&D concerns and development of the R&D program until approximately 2015 have been conducted. In parallel, concerning the prioritized concepts, perspectives on fundamental applicability have been obtained by elemental experiments and research on each of innovative technologies.

In the Phase III study and beyond, by approximately 2015, technical schemes will be developed, including preparation of data that will determine the applicability of commercial plants based on elemental test results and the presentation of technical specifications of commercial plants, with the aim of the “presentation of the commercialization picture and the R&D program required for realization”.

Throughout the duration of the timeframe, R&D will be conducted efficiently with repeated check & review at each interim summary (every 2-3 years) as well as at the end of each Phase. Further, the strategy for developing the principle and complementary concepts will be reviewed in each Phase by taking into account various situations, including trends in international development as well as the energy supply and demand conditions.

In the Phase III study, elemental experiments and research will be conducted in order to evaluate the applicability of innovative technologies, and a conceptual design study of a total system of innovative plants will be conducted. Based on results of these, it will be decided which innovative technologies should be adopted; and it may become necessary to substitute more applicable technologies (e.g., alternative technologies) for any innovative technologies presenting applicability concerns.

In the Phase IV study, elemental experiments and research on the applicability of the adopted innovative technologies as well as an optimization study of the innovative plant to be conceptually-designed in the Phase III study will be conducted to present the commercialization picture and R&D program for realization.

3.2 R&D program for FR systems

3.2.1 Sodium-cooled reactor

At the end of the Phase III study (~2010), innovative technologies to be adopted in the FR system will be decided by judging the applicability of new materials, including the ODS steel cladding and high-chromium steel, as well as of innovative components, such as an integrated intermediate heat exchanger with primary pump, a compact reactor vessel and a steam generator with double-walled heat transfer tube, and also from inspection technology prospects for components under sodium and double-walled heat transfer tubes as well as maintenance technologies, including in-service inspection (ISI) and maintenance standards, to establish a concept of a commercial reactor that excels in economy, maintainability and repairability, and other features.

Concerning oxide fuel, the irradiation of fuel pins and TRU fuel pins using the ODS cladding will be continued to reach 40-60% of the targeted fluence (250GWd/t: pin peak value) so as to confirm integrity in the initial irradiation period. While, considering metallic fuel, irradiation of TRU fuel pins under high temperature condition (650℃) will be conducted to confirm integrity in the initial irradiation period.

In the Phase IV study, based on the commercial reactor concept to be established in the Phase III study, elemental experiments on the adopted innovative technologies (including maintenance and repair technologies) will be conducted to confirm applicability, and the conceptual design will be optimized by reflecting those confirmation results.

Concerning oxide fuel, irradiation of fuel pins and TRU fuel pins using the ODS cladding will be continued to confirm integrity at the targeted fluence, and, in parallel, irradiation data will be developed for experimental data required for the commercialization. While, considering metallic fuel, irradiation integrity will be confirmed up to a high burnup, and the validity of measures to avoid recriticality will be verified by experimental research.

In the sodium-cooled reactor R&D of the GIF project, the estimated completion of the conceptual design is approximately 2010, to select a sodium-cooled reactor concept which should be subsequently developed. Aiming for this selection, efforts will be devoted to steady progress in design study as well as in elemental experiments and research, and to further cooperation with the GIF project, so as to allow the sodium-cooled reactor concept discussed in this study to be developed as an international standard.

3.2.2 Gas-cooled reactor

As the gas-cooled reactor is a complementary concept, investigation will be focused on the nitride coated particle fuel, key to the conceptual applicability. For this purpose, in the Phase III study, investigation of innovative concepts of core and fuel consisting of ceramic material will be performed by utilizing information exchange through international cooperation such as the GIF project followed by a discussion of R&D strategy based on the results. In addition, the strategy of the Phase IV study and beyond will be decided at the end of Phase III.

3.3 R&D program for fuel cycle systems

3.3.1 Combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system

In the Phase III study, innovative technologies to be adopted will be decided by judging the applicability of the crystallization process, the MA recovery, and other technologies based on small-scale hot test results. In addition, commercial component concepts will be presented in consideration of remote maintainability and repairability in the main processes. Based on these elemental experiment and research results, the commercial fuel cycle concept will be established. In parallel, the applicability of the supercritical direct extraction process, an alternative technology for the advanced aqueous reprocessing, will be carefully studied, and a judgment will be made as to whether or not it will be adopted.

In the Phase IV study, elemental experiments and research, including process tests and component development relating to innovative technologies, will be performed to develop data that will determine the technical feasibility (including remote maintainability and repairability). Using these results, an optimization study will be carried out on the conceptual design of the commercial fuel cycle facility so as to present the technical specification by the development of technical schemes (by approximately 2015). Furthermore, the concept and test program of a test facility for technology demonstration will be concretely specified, and an R&D program to achieve commercialization will be presented.

3.3.2 Combination of the metal electrorefining reprocessing system and the injection casting fuel fabrication system

As the "combination of the metal electrorefining reprocessing system and the injection casting fuel fabrication system" is a complementary concept, R&D will be conducted on an appropriate scale, with efforts to build a cooperative relationship with the USA and others. In the Phase III study, establishment of component concepts of the main processes, planning of small-scale hot tests and establishment of the commercial fuel cycle facility concept will be carried out. In addition, R&D will be conducted with a higher priority given to those problems which have less potential conformity to design requirements, including the reduction in the amount of HLW.

In the Phase IV study, it is planned that development of the main process components and preparation for small-scale hot tests will be addressed to confirm conformity to the development goals and a subsequent comparative evaluation will be performed with the principle concept at the end of the Phase IV. However, concerning the R&D strategy in the Phase IV study and beyond, review should be made by the end of the Phase III, by taking into account situations both domestically and internationally, including the establishment of cooperative relationships with the USA and other countries.

3.4 Discussion on transition into the FR cycle

In order to facilitate the smooth transition from LWRs to FRs in approximately the year 2050 and beyond, when the introduction of FRs on a commercial basis is anticipated, a long-term mass flow analysis concerning the mass balance of U, Pu, etc., has been performed to calculate the required reprocessing amount and the spent fuel stockpile from the perspective of fuel supply. In addition, in order to discuss a strategy for the achievement of the transition in a reasonable manner, the applicability of FR reprocessing technology to LWR reprocessing was discussed to identify future concerns.

The mass flow analysis was performed by assuming the fixed nuclear power capacity (58GWe) beyond 2030 and the initial deployment of a FR fleet in 2050, to obtain such conclusions as that the transition from LWRs to FRs can be achieved in approximately 60 years, and that the achievement of the transition will require the reprocessing of not only FR fuel but also LWR fuel in order to supply Pu (TRU fuel) for FRs. In such a LWR fuel reprocessing, it will be effective to employ reprocessing technology for FR fuel (the advanced aqueous reprocessing system) that can streamline the LWR reprocessing system.

As it is possible to cope with the LWR fuel reprocessing by employing the reprocessing technologies for FR fuel, it is not necessary for the moment to reexamine the R&D program described in 3.(3). However, since a discussion on a new reprocessing plant to follow the Rokkasho reprocessing plant is planned to begin in approximately 2010, it is considered effective to investigate the applicability of FR reprocessing technologies to LWR fuel reprocessing more specifically by that time.

4. Issues concerning the strategy beyond approximately 2015

In order to obtain a clearer view of whether or not the development of the technical schemes as planned by approximately 2015 would definitely lead to the introduction of a FR fleet in approximately 2050, a case study was conducted on R&D strategies beyond approximately 2015. In parallel, issues concerning R&D beyond approximately 2015 were identified.

4.1 Staged R&D of the FR cycle beyond approximately 2015 (Figure 4)

As it is extremely risky and difficult to immediately aim at the construction and operation of middle or large-scale commercial plants employing numbers of innovative technologies toward the introduction of a FR cycle fleet on a commercial basis, it is necessary to step by step increase the scale of facilities and components, and to verify conformity to the development goals as well as the feasibility and reliability of the innovative technologies. For this purpose, it is considered desirable that the entire development process be divided into three stages, i.e.: the 1st stage, to develop the technical schemes of the FR cycle until approximately 2015; the 2nd stage, to have a clear view of the commercialization by demonstrating the FR cycle technologies using a test facility for technology demonstration; and the 3rd stage, to confirm economy and the reliability as well as to accumulate operating experience by using a commercialization promotion facility aiming at the introduction of a FR fleet on a commercial basis.

4.2 Issues beyond approximately 2015

As the Government plans to begin discussions in approximately 2015 on a staged R&D program leading to FR introduction on a commercial basis in approximately 2050, discussions are required to give more concrete form to the following subjects. In particular, on the strategy in the second stage, discussions are required to be advanced by the next revision of the Framework for Nuclear Energy Policy, in which discussion of the strategy is anticipated.

i) How R&D (FR system, fuel cycle system) should be carried out in each stage

Contents, execution period, scale, required funds, and international sharing of R&D tasks in the 2nd stage (demonstration of innovative technologies) and the 3rd stage (promotion of commercialization).

ii) Sharing of roles for the development and retention of technologies after the demonstration stage

Development of an organization that considers the sharing of roles between public and private sectors (Ministry of Education, Culture, Sports, Science and Technology; Ministry of Economy, Trade and Industry; private sectors) and the retention of technologies in the 2nd and the 3rd stages.

Table 1 Development goals and design requirements

Development goal	Design requirements for FR system	Design requirements for fuel cycle system
Safety	• Occurrence frequency of core damage is less than 10^{-6} per reactor year. • Enhancement of passive safety measures against representative events possibly leading to core damage, or concretization of accident management measures • Can avoid the occurrence of recriticality during hypothetical core damage and ensure the cessation of effects inside reactor vessel or containment facility	• Equivalent or superior to the LWR fuel cycle system of the same age (eliminating occurrence factors of abnormalities to the utmost, preventing propagation of abnormalities, etc.) • Realize a design that can suppress the occurrence frequency of large release events of radioactive material in a facility to less than 10^{-6} per plant year, and assure confinement function of the facility even when assuming such an event, to produce an insignificant influence on the surrounding environment
Economic competitiveness (¥4/kWh for power generating cost as a FR cycle system)	• Construction cost: ¥200,000/kWe • Fuel cost: Core-averaged fuel burnup: 150GWd/t • Operating cost: - Continuous operation period equal to or longer than 18 months - Availability equal to or longer than 90%	• Reprocessing and fuel fabrication cost: ¥0.8/kWh • Fuel cycle cost including transportation and waste disposal fee: ¥1.1/kWh
Reduction of environmental burden	• Can accept low decontaminated TRU fuel (with ~5% of MA content) in order to allow economical burning of MA to be recovered from LWR spent fuel • Nuclear transmutation performance of long-lived FPs	• Radioactive waste volume generated per unit electricity output is required to be equivalent to or less than that of the LWR fuel cycle facility, and targeted to reduce to 1/10. • Leakage ratio of U and TRU into waste equal to or less than 0.1% (Desired) • Pursue the possibility of reducing the disposition burden by adopting partition and transmutation technology of long-lived radioactive nuclides, etc.
Efficient utilization of nuclear fuel resources	• Breeding ratio - Can achieve a breeding ratio of 1.0 or more using low decontaminated TRU fuel - In the case of a breeding ratio of 1.1 or greater, aim to increase burnup of the whole core and prolong continuous operation period, for improving economy during the transition period from LWRs to FRs • In addition to utilization as a basic power source, multi-purpose use and high thermal efficiency is possible (Desired)	• Recovery ratios of both U and TRU equal to or larger than 99%
Enhancement of nuclear non-proliferation	• Can transport and handle the low decontaminated TRU fuel, so as to limit accessibility by an increased dose	• Design that considers how to address physical protection and safeguards. • Prevention of pure Pu handling • Limit accessibility by an increased dose accompanied by the use of low decontaminated TRU fuel

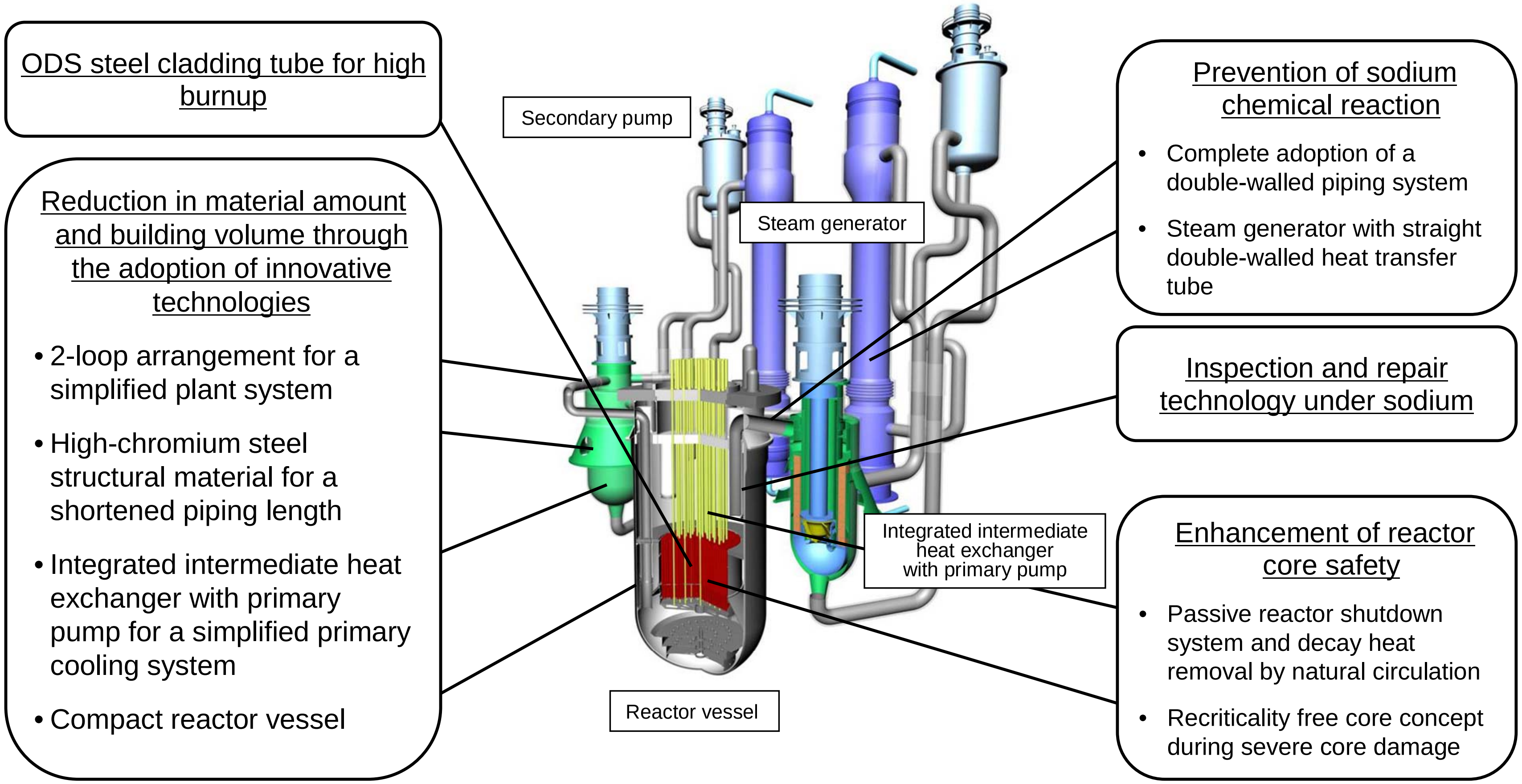
Table 2 Technical summary results for candidate concepts for FR system

Reactor type / Evaluation item	Sodium-cooled reactor	Helium gas-cooled reactor	Lead-bismuth-cooled reactor	Water-cooled reactor
Potential conformity to design requirements	Having the high level potential of meeting all the design requirements. When adopting metallic fuel, further improvement of the core performance can be expected.	Having the potential of meeting all the design requirements, as well as attractiveness as a high temperature heat source.	Having the potential of meeting all the design requirements.	Both the efficient utilization of nuclear fuel resources and the reduction of environmental burden are limited. Having the potential of meeting the other design requirements.
Technical feasibility	Possible to anticipate the feasibility with a high degree of reliability because development subjects are clear and alternative technologies can be prepared.	To anticipate the feasibility, it is necessary to solve problems that will determine the conceptual applicability.		Having concerns with anticipating the feasibility, but they are limited to the ones on core and fuel related issues.
(International viewpoint)	Possible to anticipate international cooperation. (Actively studied at GIF, and having a possibility of becoming an international standard concept. Breakthrough on innovative technologies and efficient development by sharing roles can be expected.)	Possible to anticipate international cooperation. (Having a possibility of becoming an international standard concept. When decisive problems for applicability are solved, it is possible to enhance the technical feasibility.)	Difficult to anticipate international cooperation. (No country takes leadership in the development at GIF, and hence, it is unlikely to break through decisive problems for the conceptual applicability.)	Difficult to anticipate international cooperation. (As it is not selected as a candidate concept at GIF, international cooperation is limited to basic research topics at this time.)

Table 3 Technical summary results for candidate concepts for fuel cycle system

Combination / Evaluation item	**Advanced aqueous reprocessing & Simplified pelletizing fuel fabrication**	**Metal electrorefining reprocessing & Injection casting fuel fabrication**	**Advanced aqueous reprocessing & Vibration packing fuel fabrication (*)**	**Oxide electrowinning reprocessing & Vibration packing fuel fabrication**
Potential conformity to design requirements	Having the high level potential of meeting all the design requirements, and in particular, showing better economy of large-scale facility due to scale effects.	Having the potential of meeting all the design requirements, as well as showing better economy of small-scale facility.	Having the potential of meeting all the design requirements.	Having the potential of meeting all the design requirements.
Technical feasibility	Possible to anticipate the feasibility.	Possible to anticipate the feasibility; However, it is estimated to take a relatively long time because infrastructures are required to be developed.	Possible to anticipate the feasibility.	Having numbers of technical problems and requires a long time for the development
(International viewpoint)	Possible to anticipate international cooperation. (Related investigations in hot laboratories are conducted in France, etc.)	Possible to anticipate international cooperation. (Related investigations in hot laboratories are conducted in the USA.)	Difficult to anticipate international cooperation. (No country actively promotes the development)	Possible to anticipate international cooperation. (Related investigations in hot laboratories are conducted in Russia.)

(*): The “gelation process”, a subprocess of this vibration packing process, is used for manufacturing the nitride coated particle fuel for the helium gas-cooled reactor; however, the development of the corresponding fuel cycle concept is considered to be more efficient to initiate after the nitride coated particle fuel concept would be established by the progress of the FR system development.



ODS steel cladding tube for high burnup

Reduction in material amount and building volume through the adoption of innovative technologies

- 2-loop arrangement for a simplified plant system
- High-chromium steel structural material for a shortened piping length
- Integrated intermediate heat exchanger with primary pump for a simplified primary cooling system
- Compact reactor vessel

Prevention of sodium chemical reaction

- Complete adoption of a double-walled piping system
- Steam generator with straight double-walled heat transfer tube

Inspection and repair technology under sodium

Enhancement of reactor core safety

- Passive reactor shutdown system and decay heat removal by natural circulation
- Recriticality free core concept during severe core damage

Figure 1 Concept of the sodium-cooled reactor

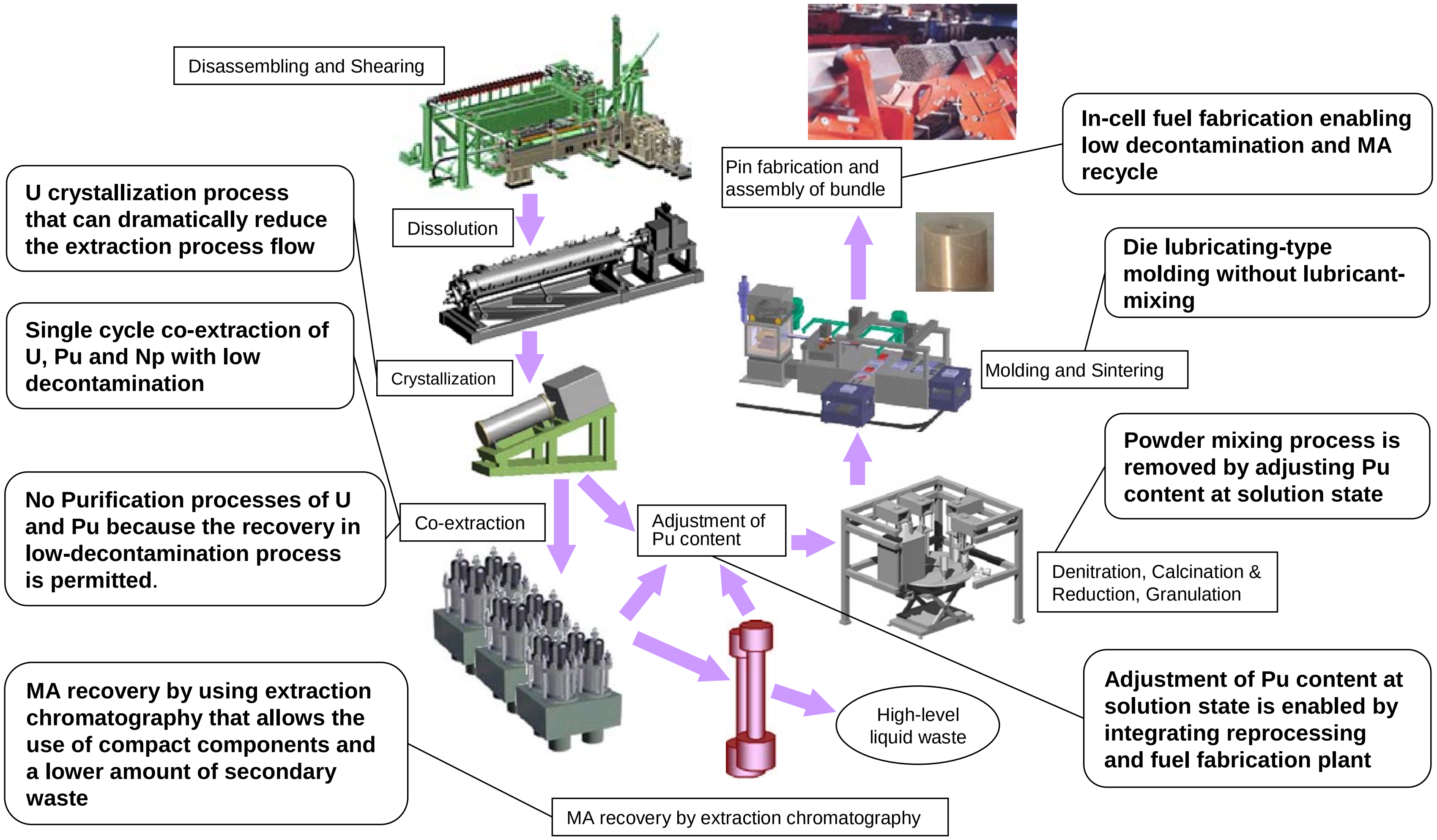
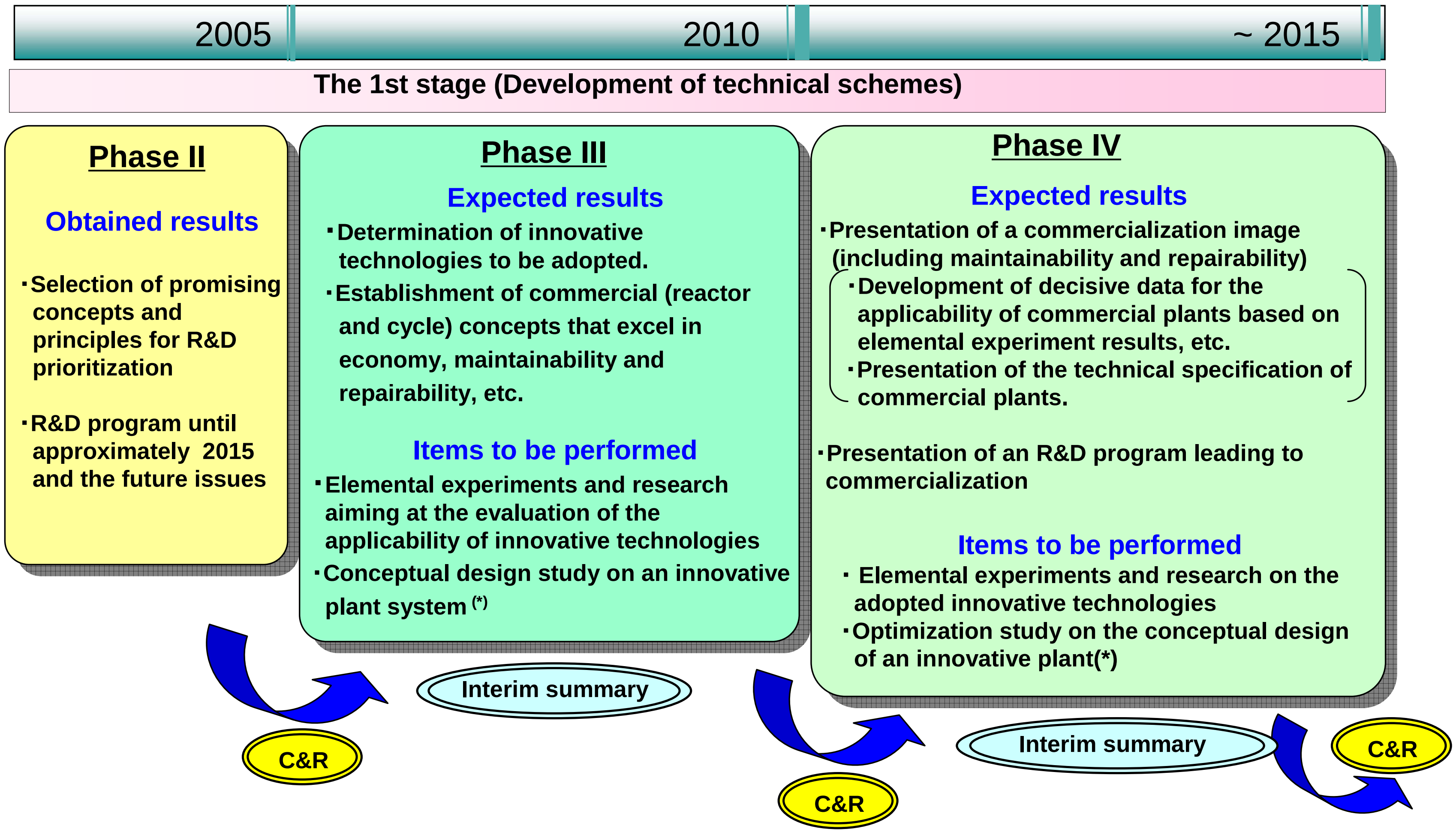


Figure 2 Concept of the combination of the advanced aqueous reprocessing system and the simplified pelletizing fuel fabrication system



2005 2010 ~ 2015

The 1st stage (Development of technical schemes)

Phase II

Obtained results

- Selection of promising concepts and principles for R&D prioritization
- R&D program until approximately 2015 and the future issues

Phase III

Expected results

- Determination of innovative technologies to be adopted.
- Establishment of commercial (reactor and cycle) concepts that excel in economy, maintainability and repairability, etc.

Items to be performed

- Elemental experiments and research aiming at the evaluation of the applicability of innovative technologies
- Conceptual design study on an innovative plant system (*)

Phase IV

Expected results

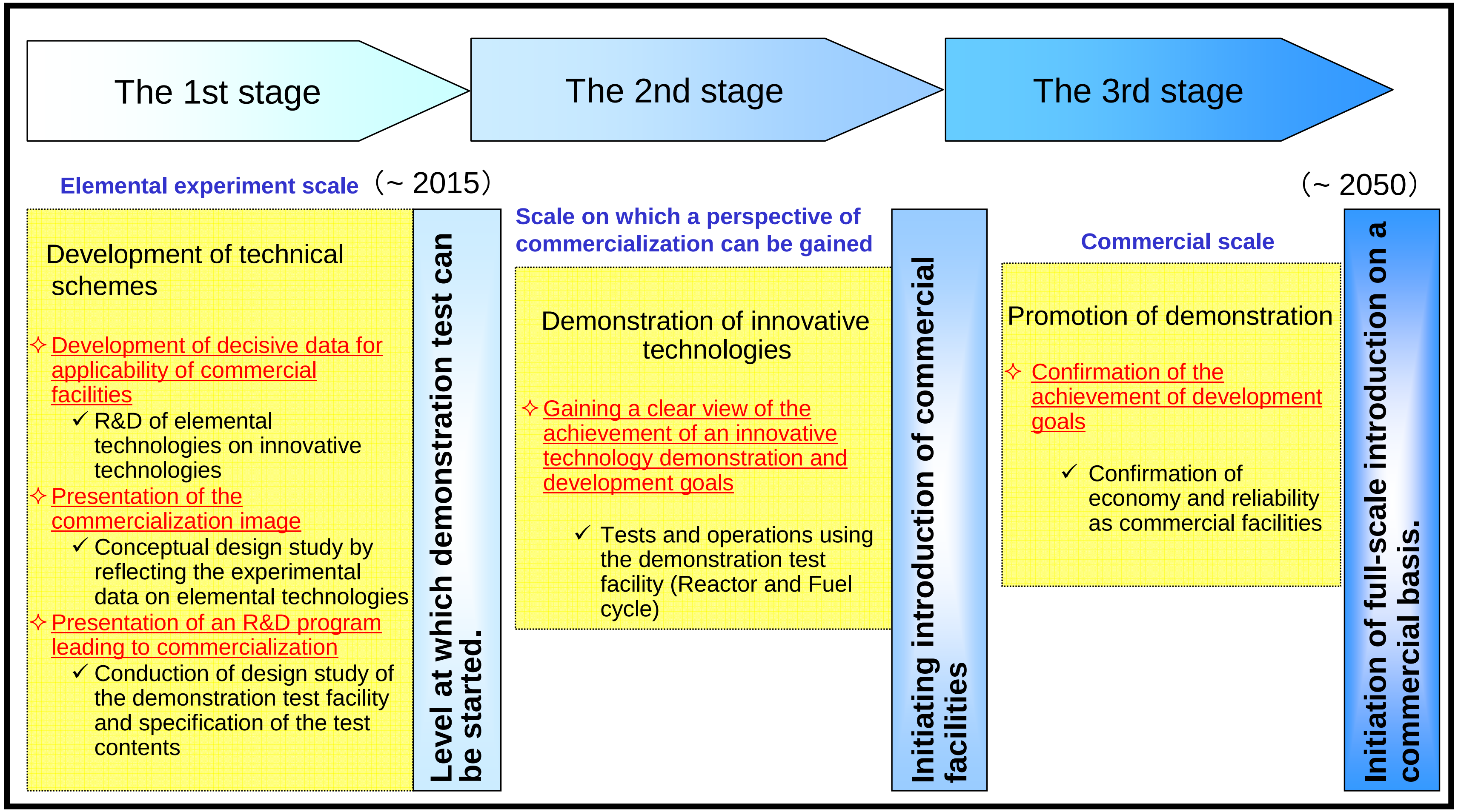
- Presentation of a commercialization image (including maintainability and repairability)
  - Development of decisive data for the applicability of commercial plants based on elemental experiment results, etc.
  - Presentation of the technical specification of commercial plants.
- Presentation of an R&D program leading to commercialization

Items to be performed

- Elemental experiments and research on the adopted innovative technologies
- Optimization study on the conceptual design of an innovative plant(*)

(*) Investigation will also be performed on the R&D strategy for the complementary concepts and the necessity of introducing basic technologies.

Figure 3 R&D prospects until approximately 2015



The 1st stage

The 2nd stage

The 3rd stage

Elemental experiment scale (~ 2015)

Development of technical schemes

✧ Development of decisive data for applicability of commercial facilities
  - ✓ R&D of elemental technologies on innovative technologies

✧ Presentation of the commercialization image
  - ✓ Conceptual design study by reflecting the experimental data on elemental technologies

✧ Presentation of an R&D program leading to commercialization
  - ✓ Conduction of design study of the demonstration test facility and specification of the test contents

Level at which demonstration test can be started.

Scale on which a perspective of commercialization can be gained

Demonstration of innovative technologies

✧ Gaining a clear view of the achievement of an innovative technology demonstration and development goals
  - ✓ Tests and operations using the demonstration test facility (Reactor and Fuel cycle)

Initiating introduction of commercial facilities

Commercial scale (~ 2050)

Promotion of demonstration

✧ Confirmation of the achievement of development goals
  - ✓ Confirmation of economy and reliability as commercial facilities

Initiation of full-scale introduction on a commercial basis.

Figure 4 Image of the staged R&D until approximately 2050

Reference Table 1 Potential conformity to design requirements of each FR system

Design requirement			Sodium-cooled reactor (1,500MWe) MOX fuel (metallic fuel)		Helium gas-cooled reactor (1,500MWe) Nitride fuel		Pb-Bi-cooled reactor (750MWe) Nitride fuel		Water-cooled reactor (1,356MWe) MOX fuel
			Breeding core	Break-even core	Breeding core	Break-even core	Breeding core	Break-even core	-
Safety			Out-of-pile and in-pile experiments are underway, concerning the passive safety mechanism and measures to avoid recriticality.		Having a possibility of avoiding recriticality by fuel expulsion caused by in-core heating and pressurization, as well as installation of the core catcher.		Having a possibility of avoiding recriticality due to fuel floating		Having a possibility of avoiding recriticality by installing absorber, etc.
Efficient utilization of nuclear fuel resources		Breeding ratio (1.0～approx. 1.2)	1.10 (1.11)	1.03 (1.03)	1.11	1.03	1.10	1.04	1.05
		Fissile fuel inventory required for the initial loading core	5.7 (4.9) t/GWe	5.8 (5.1) t/GWe	7.0 t/GWe	7.0 t/GWe	5.9 t/GWe	5.9 t/GWe	Approx. 11t/GWe
		Time required to replace all nuclear power reactors with FRs	Approx. 60 years	—	Approx. 110 years	—	Approx. 70 years	—	Approx 250 years
Reduction of environ-mental burden		MA burning	Can accept MA content up to approx. 5% that is recycled from LWR spent fuel under low decontamination condition (with FP content of 0.2 vol%).						Can accept MA content up to approx. 4% under low decontamination condition
		FP transmutation	Having a possibility of transmuting self-generating LLFP (^{129}I and ^{99}Tc), by installing the FP both inside the core and the radial blanket region.						Not yet studied.
Economic competi-tiveness	**a) b)**	In-core average (150GWd/t or higher)	147 (149) GWd/t	150 (153) GWd/t	121 GWd/t	123 GWd/t	154 GWd/t	155 GWd/t	88 GWd/t
		Whole-core average (60GWd/t or higher)	90 (134) GWd/t	115 (153) GWd/t	69 GWd/t	89 GWd/t	105 GWd/t	128 GWd/t	45 GWd/t
	c)	Operation period (18 months or longer)	26 (22) months	26 (22) months	18 months	18 months	18 months	18 months	18 months
		Availability (Calculated value) (90% or more)	Approx. 95 (94)%	Approx. 95 (94)%	Approx. 92%		Approx. 93%		Approx. 93%
	d)	Reactor outlet temperature	550℃		850℃		445℃		287℃
		Thermal efficiency / Onsite load factor	42.5% / 4%		47% / 3%		38% / 3%		35% / 3%
	e)	Unit construction cost (¥200,000/kWe or less)	Relative value：Approx. 90％		Relative value：Approx. 100％		Relative value：Approx. 100％		Relative value：Approx. 100％

a) Fuel cost reduction b) Fuel burnup c) Availability improvement d) Thermal efficiency improvement e) Capital cost reduction

* Availability (design value) = 100×operation period／(operation period + planned outage period)

Breeding core: Core specification which reduces the doubling time to breed Pu more efficiently.

Break-even core: Core specification which aims to reduce the fuel cycle cost by improving averaged fuel burnup.

Reference Table 2 Potential conformity to design requirements of each fuel cycle system

Design requirement			Design requirement Advanced aqueous reprocessing + Simplified pelletizing fuel fabrication (MOX fuel)		Metal electrorefining reprocessing + Injection casting fuel fabrication (Metallic fuel)		Advanced aqueous reprocessing ＋ Vibration packing fuel fabrication (Sphere-pack) (MOX fuel)		Oxide electrowinning reprocessing + Vibration packing fuel fabrication (Vipac) (MOX fuel)	
			Breeding core	Break-even core	Breeding core	Break-even core	Breeding core	Break-even core	Breeding core	Break-even core
Safety			Potential to meet design requirements. (Can follow existing guidelines, etc.) ※Supercritical direct extraction process needs a design considering the treatment of high-pressure fluid to have a potential conformity to design requirements.		Potential to meet design requirements. (Design that considers treatment of high-temperature melt, active metal, etc., as well as the criticality control by combining the mass control and chemical form control)		Potential to meet design requirements. (Can follow existing guidelines, etc.)		Potential to meet design requirements. （Design that considers treatment of chlorine gas, high-temperature melt, active metal, etc.）	
Economic competitiveness	**a)**	Large-scale plant [200t/y]	Approx. 60%	Approx. 45%	Approx. 65%	Approx. 55%	Approx. 80%	Approx. 65%		
		Small-scale plant[50t/y] (Supercritical direct extraction process）	Approx. 135% （Approx. 120%）	Approx. 105% （Approx. 95%）	Approx. 80%	Approx. 75%			Approx. 110%	Approx. 90%
	b)	Large-scale and small-scale plants (Supercritical direct extraction process）	Approx. 100% （Approx. 95%）	Approx. 95% （Approx. 90%）	Approx. 145%	Approx. 140%	Approx. 100%	Approx. 95%	Approx. 120%	Approx. 110%
	c)	Large-scale plant [200t/y]	Approx. 70%	Approx. 60%	Approx. 85%	Approx. 80%	Approx. 85%	Approx. 75%		
		Small-scale plant [50t/y] (Supercritical direct extraction process）	Approx. 125% （Approx. 115%）	Approx. 100% （Approx. 95%）	Approx. 100%	Approx. 90%			Approx. 115%	Approx. 95%
Efficient utilization of nuclear fuel resources		Recovery ratio of U and TRU ≧99%	A design that can recover 99% or more of U and TRU is estimated to be possible by basic test data.						Possible to be designed. (Confirmation of the MA recovery ratio is required.	
Reduction of environmental burden	**Reprocessing**	Volume of HLW ≦0.5L/GWh	Borosilicate glass: Approx. 60%		Glass-bonded sodalite: Approx. 110%		Borosilicate glass: Approx. 60%		Phosphate glass, Alloy: Approx. 80%	
		Amount of TRU and high β/γ wastes≦1.6L/GWh	Approx. 85%		Approx. 35%		Approx. 85%		Approx. 60%	
Enhancement of nuclear non-proliferation		Prevention of pure Pu handling	Co-recovery of U , Pu and Np		Co-recovery of U and TRU		Co-recovery of U , Pu and Np		Co-recovery of U and Pu	
		Assuring difficulty in accessibility	Assuring difficulty in accessibility by low decontamination							

a) (Reprocessing + Fuel fabrication) cost ≦ ¥0.8 /kWh b) Transportation/Storage/Waste disposal cost ≦ ¥0.3/kWh c) Fuel cycle cost ≦ ¥1.1/kWh

Reference Table 3 Improvement in core performance by the employment of metallic fuel

Breeding ratio		1.03(1.03)	1.11(1.10)	1.19(1.20)	1.26
Fissile fuel amount required for the initial loading core		5.1 (5.8)t/GWe	4.9 (5.7) t/GWe	3.9 (4.4)t/GWe	3.9t/GWe
Burnup	Average in the core fuel region	153 (150) GWd/t	149 (147) GWd/t	95 (154) GWd/t	96 GWd/t
	Average in the whole core (including the blanket region)	153 (115) GWd/t	134 (90) GWd/t	65 (55) GWd/t	55 GWd/t
Operation period		~ 22 (26) months	~ 22 (26) months	~ 22 (18) months	~ 22 months
Feature		The whole-core-averaged burnup is higher than that of MOX fuelled core by approximately 30%.	The whole-core-averaged burnup is higher than that of MOX fuelled core by approximately 50%.	The whole-core-averaged burnup is higher than that of MOX fuelled core by approximately 20%.	When compared with LWRs, higher breeding ratio is achievable under equivalent burnup.

Values in (   ) are estimated on MOX-fuelled cores. (Design condition of the reactor outlet temperature is 550℃.)

○ Metallic-fuelled cores (Design condition: Reactor outlet temperature=550℃, Operation period =22 months) can

- **achieve a breeding ratio of approx. 1.26 at maximum (approx. 1.20 for MOX-fuelled cores) under burnup equivalent to LWRs. (It is necessary to confirm the applicability of such thermal designs in the future.)**
- **improve burnup by 20-50% compared with those of MOX-fuelled cores under the breeding ratio of approx. 1.20 or below, as well as decrease the initially-loading fissile fuel amount by 10% or more.**

○ It is estimated by a long-term mass flow analysis on the transition into the FR era that, for instance, assuming the initiation of FR introduction in 2030, metallic-fuelled core (breeding ratio of 1.26) can reduce the cumulative demand amount of natural uranium by approx. 20% compared with MOX-fuelled core (breeding ratio of 1.20).

Reference Table 4 Combinations of the reprocessing and fuel fabrication systems as well as the FR systems and the corresponding fuel types, on which Phase II studies were performed.

Fuel fabrication system / Reprocessing system	Simplified pelletizing	Vibration packing	Injection casting	Coated particle
Advanced aqueous	O Na O W N Pb	O Na	–	N He
Oxide electrowinning	–	O Na	–	–
Metal electrorefining	N Pb	–	M Na	–

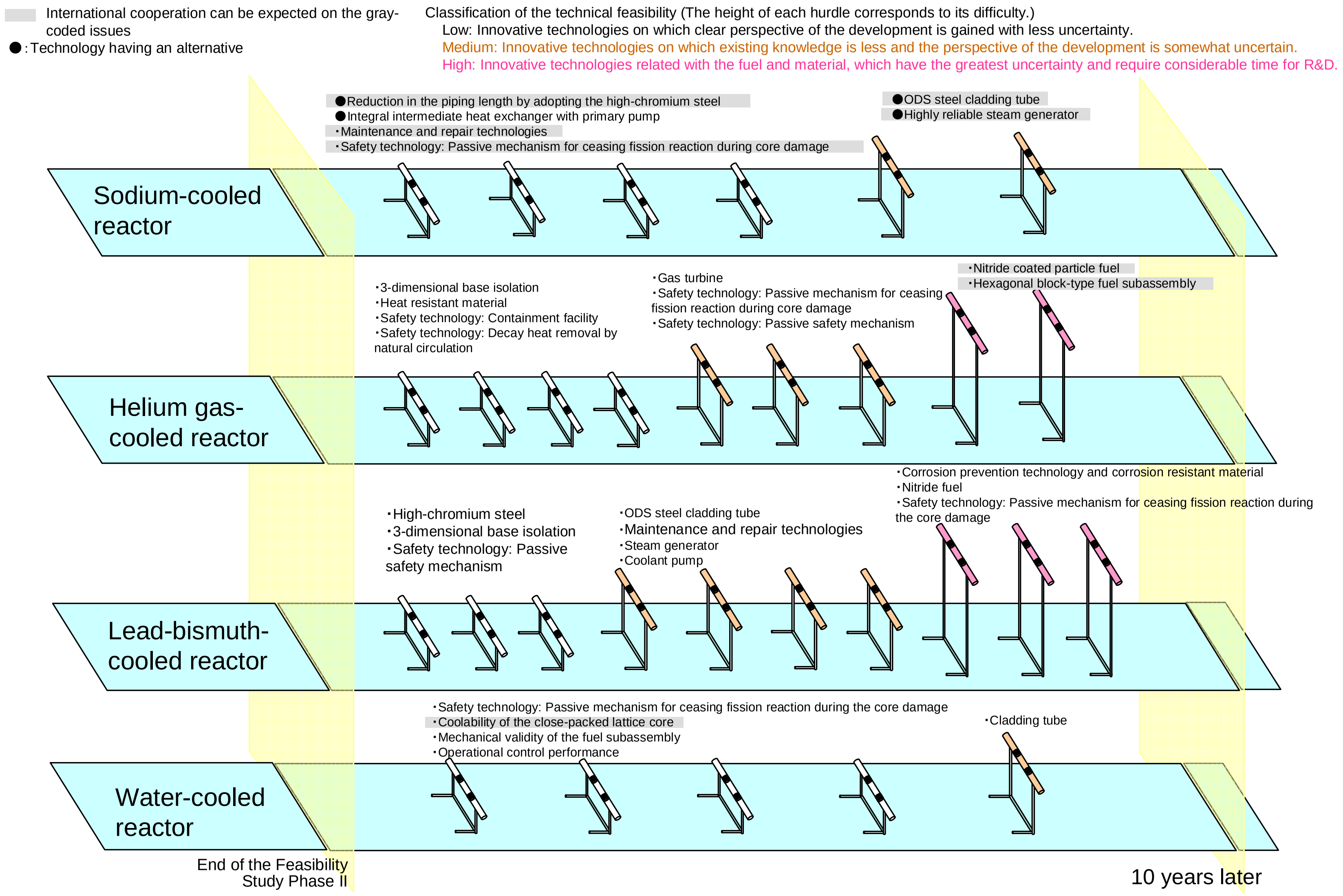
O Oxide fuel (MOX fuel)
M Metallic fuel
N Nitride fuel
To be applicable by adding processes including ^{15}N-enriched nitrogen recovery and nitriding processes

Na Sodium-cooled reactor
He Helium gas-cooled reactor
Pb Lead-Bismuth-cooled reactor
W Water-cooled reactor

Reference Table 5 Potential conformity to design requirements as the entire FR cycle system

Studied concept			Potential conformity to design requirements				
	FR system	**Fuel cycle system**	**Safety**	**Economic competitiveness** (Power generating cost is equal to or lower than that of future LWRs.)	**Reduction of environmental burden** (Reduction in radioactive waste amounts and the potential hazard due to radioactivity (1000 years later), as well as acceptability of MA from LWRs)	**Efficient utilization of nuclear fuel resources** (cumulative demand amount of natural uranium up to the completion of transition from LWRs to FBRs)	**Enhancement of nuclear non-proliferation**
(1)	**Sodium-cooled reactor (MOX fuel)**	**Advanced aqueous reprocessing** **＋** **Simplified pelletizing fuel fabrication**	Perspective of assuring safety against design basis events, as well as beyond design basis accidents is confirmed.	Approx. 60% (*1)	・Amount of HLW 1.0 (relative value） (*2) ・Amount of LLW 1.0 (relative value） (*2) ・Potential hazard due to radioactivity (1000 years later) 1.0 (relative value） (*2) ・Possible to accept MA from LWRs	Approx. 5% of conventional resources of natural uranium	Low decontaminated TRU fuel cycle Co-recovery of U, Pu and Np.
(2)	**Sodium-cooled reactor (Metallicfuel)**	**Metal electrorefining reprocessing** **＋** **Injection casting fuel fabrication**	Perspective of assuring safety against design basis events, as well as beyond design basis accidents is confirmed.	Approx. 70% (*1)	・Amount of HLW 1.7 (relative value） (*2) ・Amount of LLW 1.0 (relative value） (*2) ・Potential hazard due to radioactivity (1000 years later) 2.1 (relative value） (*2) ・Possible to accept MA from LWRs	Approx. 5% of conventional resources of natural uranium	Low decontaminated TRU fuel cycle Co-recovery of U and TRU
(3)	**Helium gas-cooled reactor (Nitride coated particle fuel)**	**Advanced aqueous reprocessing ＋ Coated particle fuel fabrication (Sphere-pack)**	Perspective of assuring safety against design basis events, as well as beyond design basis accidents is confirmed.	Approx. 70% (*1)	・Amount of HLW 0.9 (relative value） (*2) ・Amount of LLW 2.1 (relative value） (*2) ・Potential hazard due to radioactivity (1000 years later) 1.4 (relative value） (*2) ・Possible to accept MA from LWRs	Approx. 6% of conventional resources of natural uranium	Low decontaminated TRU fuel cycle Co-recovery of U, Pu and Np

*1: Relative percentage to a power generating cost of future LWRs . (Breeding core)
*2: Relative values calculated by assuming the waste amounts and potential hazard due to radioactivity of (a) be 1.



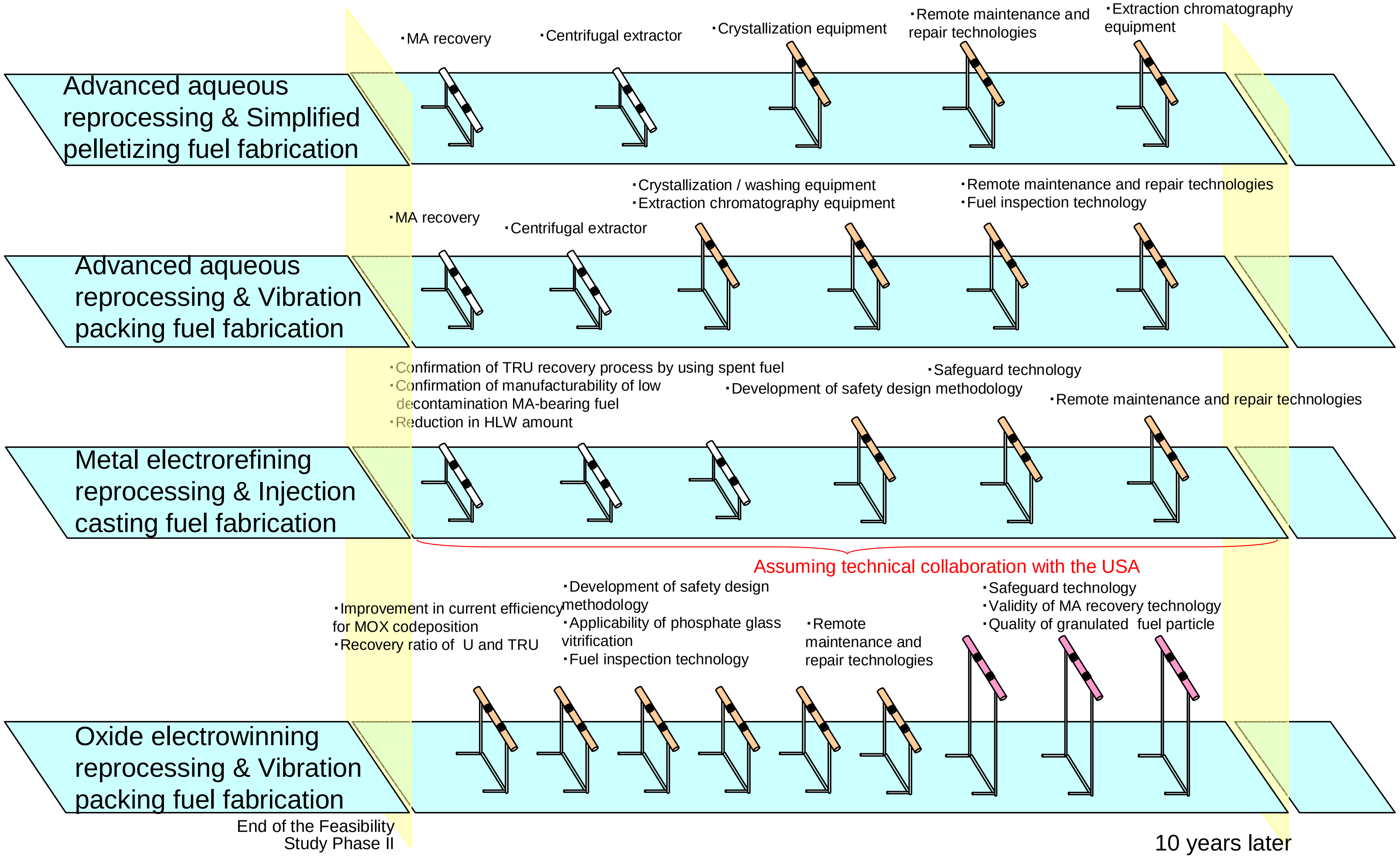
Reference Figure 1 Technical feasibility of each FR system

Classification of the technical feasibility (The height of each hurdle corresponds to its difficulty.)

Low: Innovative technologies on which a clear perspective of the development is gained with less uncertainty.

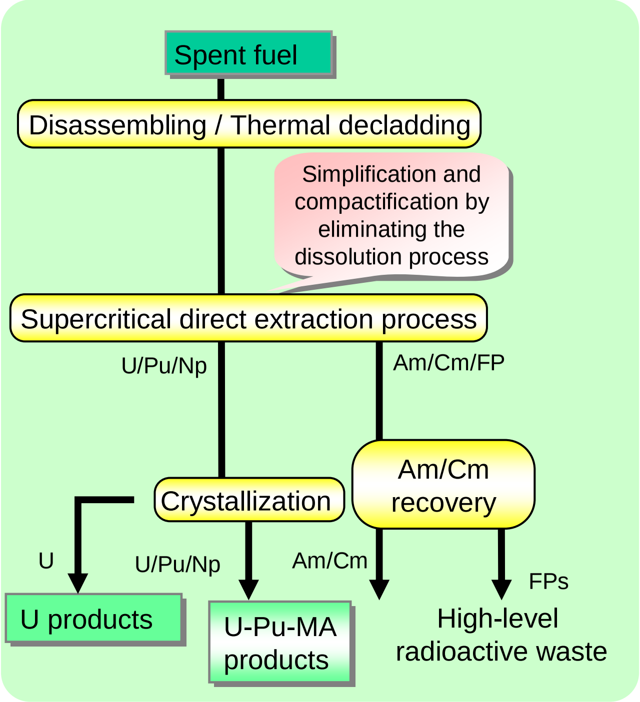
Medium: Innovative technologies on which existing knowledge is less and perspective of the development is somewhat uncertain.

High: Innovative technologies related with the fuel and material, which have the greatest uncertainty and require considerable time for R&D.

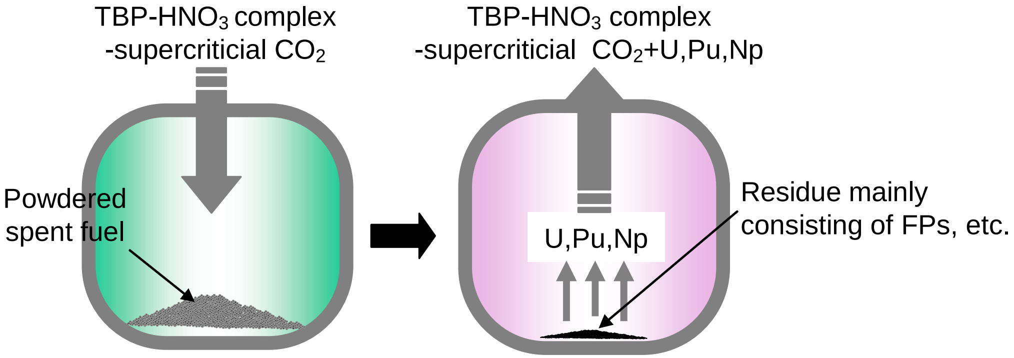


Reference Figure 2 Technical feasibility of each fuel cycle system

Advanced aqueous system using the supercritical direct extraction process



Principle of the supercritical direct extraction process



- ➢ From powdered spent fuel,
- ➢ Without applying dissolution process,
- ➢ Into supercritical CO$_2$ gas containing TBP-HNO$_3$complex,
- ➢ Directly extract U-Pu-Np.

⇒Possibility of improving economy through simplified process

Present status of the technology development

- ➢ At a stage in which the principle is confirmed by beaker-scale tests using spent fuel.
- ➢ Already commercialized in general industries in, for example, the extraction of caffeine from coffee beans.

Reference Figure 3 Supercritical direct extraction process