A Study on the Gaps and Pathways to a Fusion DEMO

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Abstract

An exploratory study on gaps and pathways to a fusion demonstration plant of Korea (K-DEMO) has been carried out by referring to the frame of references developed based on the postulation of the commonalities of a fusion power plant with the nuclear power plants (NPPs) in the design process and methodologies, and operational characteristics. In the pathways to K-DEMO, cross-cuttings with the fusion R&D activities of the other countries and utilizing the commonalities with the NPPs are discussed with the provision of open-innovation strategy that is one of the key strategies of K-DEMO program.

1. Frame of References for the Identification of the Gaps to K-DEMO

As a fusion demonstration plant (DEMO) does not exist, and its design processes and design methodologies have not been fully developed, frame of references to study gaps and pathways to DEMO should be determined. To define the frame of references to study the gaps and pathways to DEMO, it is postulated that the design processes and operational characteristics of the nuclear power plants (NPPs), among the existing energy production systems, have sufficient commonalities with DEMO.

1.1 Postulated Operating Modes and Characteristics of K-DEMO

For the purpose of a qualitative scaling of the expected achievement of the magnetic fusion energy (MFE) devices with the tokamak concept, in consideration of the normal operating modes of the NPPs of Korea, the operating modes of the fusion reactor of K-DEMO (K-DEMO reactor) were hypothetically defined and shown in Table 1.

To be a power reactor, regardless of a long pulse operation [1] or steady-state operation [2] the reactor of DEMO will have to be as follows:

- It should be maneuverable from cold-shut-down (CSD) to hot-full-power (HFP) at the maximum ramp-up rate of less than 5% per minute of the rated full power in a controlled way;

- As the number of the reactor trips are limited in the NPPs to protect the structures, systems, and components (SSCs) of the reactor, that of plasma quenches shall not exceed a prescribed limit to maintain the integrity of the SSCs of the K-DEMO reactor;
- The K-DEMO reactor should be maintained at the rated 100% power for a couple of days;
- Maneuvering of the fusion reactor from CSD to HZP and from HZP to CSD should be so slow as to be completed in 24 hours or more to minimize the excessive stresses to the SSCs of the K-DEMO reactor;
- The cumulative magneto-hydro-dynamic (MHD) loads and thermo-hydraulic (T-H) loads incurred by the transitional operations shall not exceed the allowable stresses of the SSCs of K–DEMO reactor.

Table 1: Postulated Operating Modes of K-DEMO Reactor

<table>
<tr><th>Operating Modes</th><th>Definition</th><th>Remarks</th></tr>
<tr><td>Cold-shut-down (CSD)</td><td>• The pressure and temperature of the reactor coolant system (RCS) at the atmospheric pressure and below boiling temperature;
• The magnets and heating and current drive mechanisms (H&CD) de-energized;
• Vacuum not established.</td><td rowspan="4">Equivalent to CSD, HSB, HZP, and HFP of the NPPs respectively</td></tr>
<tr><td>Hot-stand-by (HSB)</td><td>• The pressure and temperature of RCS at or near that of the atmospheric pressure and below boiling temperature;
• The magnets and H&CD energized;
• Vacuum fully established;
• D-D plasma in a steady state operation.</td></tr>
<tr><td>Hot-zero-power (HZP)</td><td>• D-T reaction triggered;
• The reactor power at the range of 0-5% of the rated power. D-D plasma in a steady state operation.</td></tr>
<tr><td>Hot-full-power (HFP)</td><td>• The reactor at the 100% full power.</td></tr>
</table>

1.2 Design Processes of the NPPs and K-DEMO

The design processes of the NPPs were reviewed and typical design processes shown in Figure 1 were derived [3] to use them for the identification of the gaps to be filled on the pathways to the design of K-DEMO.

To verify and validate the materials and design methods that will be used for the design and fabrication of the SSCs of K-DEMO, the test facilities should provide the following characteristics:

- Sustaining heat loads of 10 MW/m^2 at the peak and 2 MW/m^2 at average (If a power peaking will be considered the instantaneous heat loads will be doubled);

- A 14-MeV neutron source with a fluence of 10^{25} neutrons/m^2 over a sufficiently large area to test the SSCs of K-DEMO.

Due to the fact that the heat loads and neutron flux required to test the SSCs of K-DEMO cannot be provided with conventional methods, a nested logic dilemma of '*which one comes first the materials and validation of the design methodologies of K-DEMO or K-DEMO itself*' will occur as K-DEMO will be a first-of-a-kind. To resolve this dilemma, the staged K-DEMOs were planned as discussed in the next section 1.3 [4]. The processes for developing K-DEMO depicted in Figure 1 were also developed [3] to overcome this nested logic dilemma based on the commonalities of a fusion power plant with the nuclear power plants (NPPs) in the design process and methodologies, and operational characteristics [5-7].

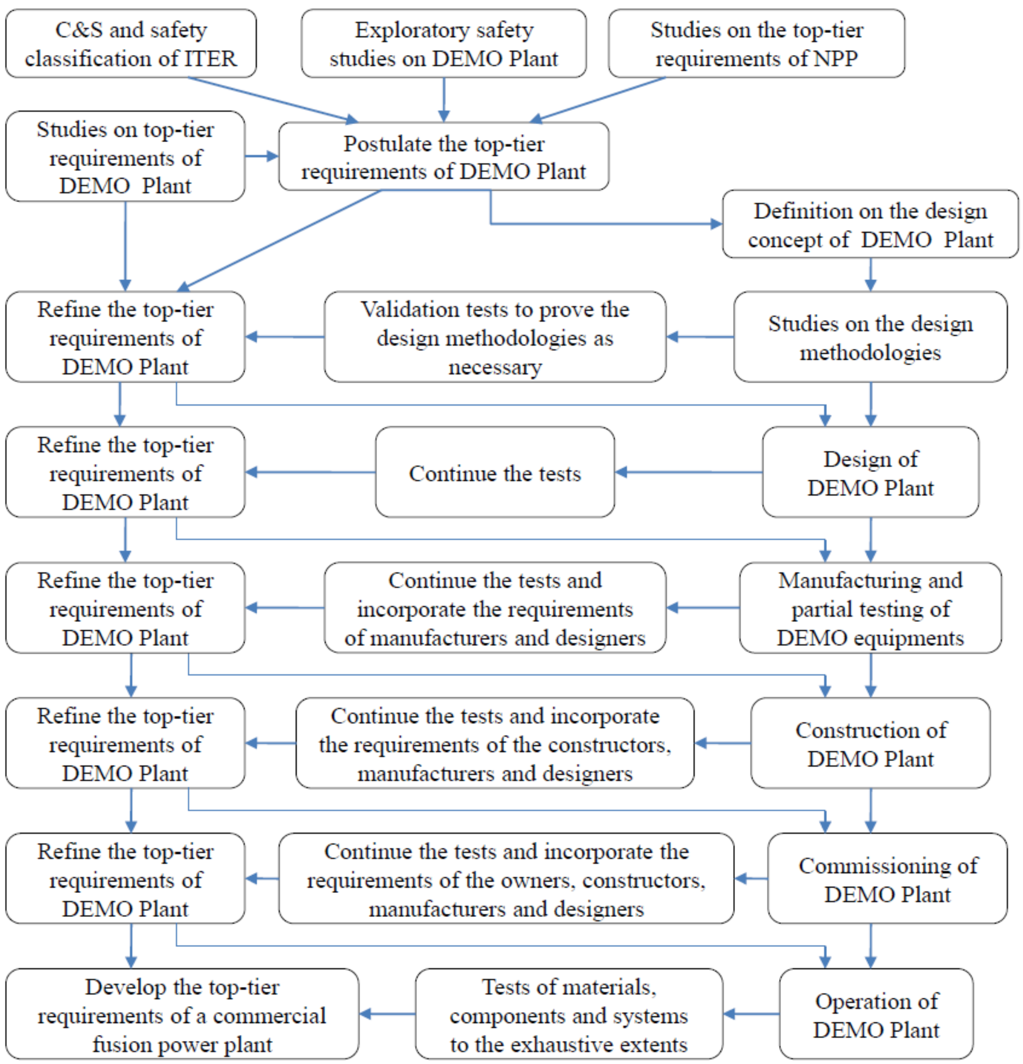

Figure 1: Proposed Processes for Developing K-DEMO [3].

1.3 Operating Definition of K-DEMO

K-DEMO will be developed in two stages such that its economic feasibility will be verified in the first stage K-DEMO (K-DEMO1) and its economic feasibility will be validated in the second stage K-DEMO (K-DEMO2) [8]. K-DEMO1 will be operated at the 10% of the rated 100% power and with 20% availability [9]. The operating parameters of the two K-DEMOs, developed using a system code [10], are shown in Table 2. The concept of K-DEMO1 is similar to that of the pilot plant (PP) [11] and fusion science technology facility (FNSF) [12].

Table 2: Operating Parameters of the Reactors of K-DEMOs

Design Parameters	**1st Stage**	**2nd Stage**
Rated power	60 MWe	600 MWe
Availability	~10 %	> 50 %
Fusion power	0.2 GW	2 GW
Average neutron wall load	0.2 MW/m^2	2 MW/m^2
Divertor peak heat load	1 MW/m^2	10 MW/m^2
RCS* temperature T_{in} (℃) / T_{out} (℃)	290 / 330	TBD
Reactor coolant	Pressurized water	
Thermal cycle	Rankine/Saturated Steam	
Postulated irradiation damage in displacements per atom (dpa)	4 dpa	200 dpa

2. Gaps and Pathways for the Control of K-DEMO Reactor

2.1 Expected Achievements of the Fusion Devices

If the achievements of the fusion experimental devices either under operation, construction, or conceptualization will be scaled in the postulated operating modes of Table 1 they are expected to be as follows [9]:

- In KSTAR, EAST and JT60-SA, it is expected that control of HSB will be achieved. It is also expected that the achievements in these devices will be extrapolated to get insight into HZP mode of operation;

- In ITER, experimental data required for developing a prototype model of the reactor kinetics and control will be obtained. However, due to its operating target of 400 seconds, the steady state operation of a fusion reactor even at HZP will not be verified and validated.

- For the Pilot Plant FNSF that may not have a proven algorithm for the instrumentation and control of their fusion reactor, even though they are to go beyond the achievement of ITER, their achievement are to be strongly dependent upon outcomes of ITER;

- The kinetics and control model, and instrumentation and control system of K-DEMO is not to be even studied at this time shall be developed with the analysis and simulation of the experimental data obtained from these experimental devices.

These expected achievements of the fusion research devices are summarized in Figure 2 [9].

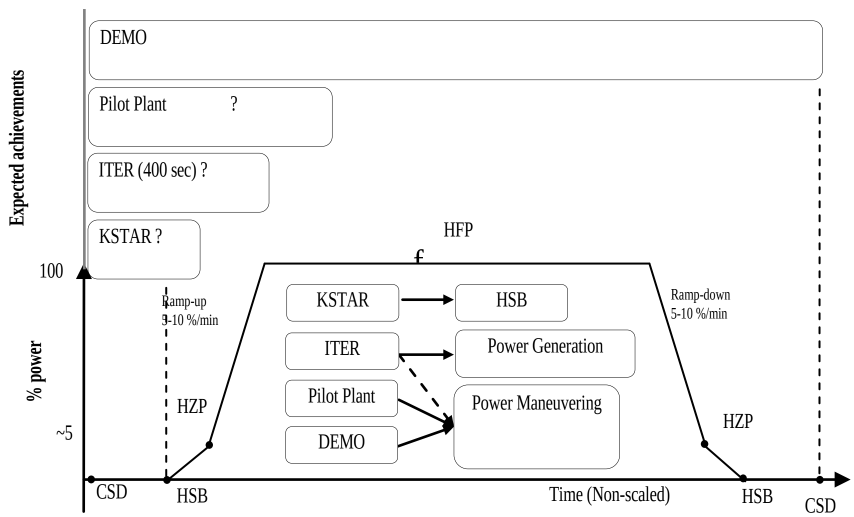

Figure 2: Expected achievement of the experimental devices [9]

2.2 Gaps and Pathways to the Control of the K-DEMO Reactor of the Fusion Devices

In referring to the postulated operating modes summarized in Table 1 and expected achievement of the fusion devices depicted in Figure 2 the technologies for the control of a fusion reactor is somewhere in between CSD and HSB.

The pathways for the development of the control system of K-DEMO reactor to fill these gaps are as follows [9]:

- The outcomes of KSTAR are to be analyzed to develop a preliminary kinetics-and-control model of fusion plasma without D-T reactions in consideration of the experimental results of tokamaks under operation;

- This model that is developed based on the experiments of tokamaks will be valid up to HSB and, even though it will not be exhaustive, to forecast the kinetics of the entrance range of HZP;

- The outcomes of physics studies and CODAC (Control, Data Access and Communication) of ITER before igniting D-T reactions are to be utilized for the verification and validation (V&V) of the kinetics model for fusion plasma developed in KSTAR;

- The experimental results of ITER D-T operations will be used for the development of a preliminary kinetics model for fusion plasma of HZP and power maneuvering of K-DEMO;

- PP, if realized, will be an experimental device that will used for V&V of the kinetics model developed in ITER;

- FNSF, if it will obtain desired performance with the copper magnets, will be also used for V&V of the kinetics model developed in ITER;

- With all these accomplishments and outcomes, the control system of K-DEMO reactor will be developed;

- V&V of the fusion power reactor will be carried out while starting up and operating of K-DEMO reactor;

- The experimental results of the other tokamaks, especially that with superconductor magnets, are to be useful for the development of the control model;

- The super-computing-based simulation studies on fusion plasma will provide some insights for developing the control model for K-DEMO reactor.

3. Gaps and Pathways of the Other Issues

3.1 Tritium Breeding

The possibility of the self-sufficiency of tritium fuel cycle in a fusion reactor was proved with analysis using the existing computational codes and current nuclear database [13]. However, with the experiments of the self-sufficiency of tritium fuel cycle including that of the test banker modules (TBM) of ITER, the codes and databases that will be used for the design of the K-

DEMO reactor should be verified and validated. If the results of ITER TBM will not be sufficient for the verification and validation (V&V) of the codes and acquisition of the nuclear data in-pile tests of the breeding blanket of K-DEMO reactor will be carried out in PP, FNSF, or K-DEMO itself.

3.2 Design of the SSCs of K-DEMO Reactor

With the studies on the regulatory requirements and C&S applicable for the development of K-DEMO1 reactor, a way of developing them through the iterative processes of designing, manufacturing, testing, constructing, and even operation of K-DEMO1 reactor [3]. The gaps and pathways discovered for the system design of K-DEMO1 reactor were as follows:

- Completion of the stress analysis for the piping systems, supporting structure, and components of K-DEMO incorporating the loads incurred by the operation of K-DEMO1 will be required to assure the safe operation of K-DEMO reactor;

- Design of the engineered safety features, to meet the inherent and passive safety of K-DEMO reactor in accordance with the results of the safety analysis and in compliance with the C&S for MFE will have to be carried out to mitigate the postulated accidents in K-DEMO reactor;

- Improvements of the superconductor magnets and H&CD (Heating and Current Drive) mechanisms will be required to sustain D-T reactions in K-DEMO reactor and R&D activities for these devices are to be carried out in the second campus of NFRI (National Fusion Research Institute) to achieve the reactor control.

3.3 Structural Integrity of In-vessel Components

In addition to the structural design of K-DEMO reactor, the structural integrity of the SSCs exposed to a high fluence of 14-Mev neutrons in the vacuum vessel under the presence of helium shall be addressed. However, irradiation damage of materials will not be adequately tested until the irradiation area of IFMIF will be increased [14]. Further, to test the structural integrity of in-vessel components, a large 14-MeV neutron source such as FNSF, PP, and K-DEMO1 itself will be required.

To overcome this dilemma, the structural materials will be irradiated to get a damage of 4 dpa in a multi-purpose research reactor called HANARO (High flux Advanced Neutron Application Reactor) [15] before they will be irradiated with 14-MeV neutrons under the presence of helium with high temperature.

3.4 Radiation Protection

As tritium is expected to be the major contributor to the source-terms of a fusion reactor [16] and K-DEMO plant as well [9] the studies on tritium inventories and behaviors in a DEMO reactor will be required for the radiation protection design of K-DEMO. Except this tritium abundant source term, the databases and computational codes are expected good for the design of K-DEMO1.

3.5 Safety and Licensing

The exploratory studies on the safety and licensing of K-DEMO plant [3, 5, 18], the gaps and pathways to K-DEMO are as follows:

- The top-tier requirements of K-DEMO1, including the regulatory requirements, C&S, quality assurance requirements should be developed to design, fabricate, construct, and operate it;
- The methodologies for the safety analysis of K-DEMO reactor will be verified and validated;
- The consequences of the explosions incurred by dust of heavy metals [17] and hydrogen generation will be tested and quantified;
- The inherent safety of K-DEMO reactor will be verified and validated, and the kinetics and control algorithm for K-DEMO reactor are to be developed.

As it is shown in Figure 1, the top-tier requirements will be developed in parallel with design, fabrication, testing, construction, and operation of K-DEMO itself: As K-DEMO will be a first-of-a-kind, V&V for the top-tier requirements will be carried out in K-DEMO through iterative processes as it is a first-of-a-kind [8].

4. Conclusion

The gap that exists in the control of K-DEMO reactor is to be the most crucial for the successful realization of MFE. The celebrated ground-break of the ITER project ushered in a new turning point in the peaceful use of nuclear-fusion-energy and will provide a key for resolving technical issues on the control of a fusion reactor. FNSF, PP, and 1st phase K-DEMO plant that will be operated after D-T operation of ITER will contribute to the realization of MFE. As the concepts and areas of research of FNSF, PP, and K-DEMO1 are not clearly distinctive, collaboration in the global contexts to make one single project, namely a pilot plant for MFE, will be required to mitigate the risks associated with developing MFE.

The cross cutting with the existing systems that have commonalities with MFE should be maximized not to lose an opportunity of cost savings and expediting the realization of MFE. In this perspective, as it already happened in ITER [6], researches on MFE should be benefited from the best use of the regulations, engineering methodologies, nuclear databases, knowledge, reference data, and even lessons learned from NPPs and development of the generation IV nuclear reactors.

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