Cross-Cutting Ideas for a Fusion DEMO Plant with Current and Generation IV Nuclear Power Plants*)

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The fusion DEMO program of Korea has been conceptualized to realize magnetic fusion energy with the tokamak concept at the end of 2030 s or early 2040 s. In this program, to expedite the development of a fusion DEMO plant, cross-cutting based on the commonalities between the fusion DEMO plant and existing systems. Among the existing systems, the current and generation IV nuclear power plants will have many areas of commonalities with the fusion DEMO plant including regulatory requirements and licensing processes, codes and standards, design methods and computational codes for thermo hydraulic analysis, and safety analysis methods. Theses commonalities will be used for discovering a pathway of resolving the nested logic dilemma incurred by the inherent first-of-a-kind nature of the fusion DEMO plant. This paper presents the result of an exploratory study on the subject cross-cutting.

Keywords: cross-cutting, fusion DEMO, commonalities, risk mitigation

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1. Pathways to Fusion DEMO Plants

Ever since the beginning of the ancient civilization, human beings have obtained energy from natural resources to enhance their welfare and sustain economic growth. On the opposite side of enhancing welfare, adverse effects such as global warming and accumulation of high-level radio-active waste have been brought about. Fusion energy is known to be comparatively less toxic than any other large-scale energy resources that have been, at least, proved in the lab-scale experiments. However, there still are technology barriers to break through to realize fusion energy

Many pathways to develop a fusion DEMO plant and commercial fusion power plant to realize magnetic fusion energy (MFE) with the tokamak concept have been proposed and discussed. Some researchers have discussed that the prerequisites to DEMO will be ITER for the discovery of physics of fusion plasma and IFMIF for the material development in addition to continuing research in the existing tokamaks. Some others have proposed the component test facility [1–3] or Pilot Plant [4], in addition to ITER, on the pathway to DEMO to verify and validate the nuclear fusion technologies that are to be used for the design, fabrication, construction, and operation of DEMO. A few have proposed staged development of DEMO. The first stage will be for the technical feasibility and the next stage for the economic feasibilities in consideration of the most significant gap for the development of MFE will be verification of kinetics and control In addition to these pathways, some have proposed fissionfusion hybrids and accelerator driven hybrids to expedite the realization of MFE [5, 6].

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2. Significant Gaps on the Pathway

In the fusion DEMO program of Korea (K-DEMO program), one of the most significant gaps to be filled on the pathway to DEMO is considered to be the kinetics and control model of the fusion reactor of K-DEMO (K-DEMO reactor). Without this model, the instrumentation and control (I&C) system of K-DEMO reactor will not be designed and operated.

2.1 Postulated operating conditions

To measure the gaps to be filled to discover the kinetics and control model of K-DEMO reactor, the four (4) normal operating modes of fusion power reactors are defined as follows:

- Cold-shut-down (CSD) will be the condition that the reactor coolant system (RCS) will be at the atmospheric pressure and below boiling temperature; the magnets and heating and current drive mechanisms (H&CD) will be energized; and vacuum is not to be established;
- Hot-stand-by (HSB) will be the condition that the operating temperature of RCS will be at or near the RCS temperature of Table 1; the magnets and H&CD will be energized and in operation; vacuum will be fully established; and D-D plasma will be in a steady state operation;
- Hot-zero-power (HZP) will be the condition that D-T reactions will be triggered; and the reactor power will

be at the range of 0-5% of the full power;
- Hot-full-power (HFP): the reactor power will be at the rated full power.

2.2 Maneuverability of a power reactor

To demonstrate power generation, flawless maneuverability of K-DEMO reactor shall be proved as to ascend the reactor power from CSD to HFP and descend HFP to CSD in a controlled way. If there will not be sudden technological jumps in the materials, structural design, thermo-hydraulics, and magneto-hydro dynamics the flawless maneuverability should meet at least the following conditions:

- Number of plasma quenches shall not exceed a certain prescribed limit to maintain cumulative stresses incurred by the transient loads not to exceed the allowable stresses of the mechanical and piping systems of K–DEMO reactor;
- Also for this purpose, as the fusion reactor will generate unexceptionally high thermal-flux, the local power peaking of K-DEMO reactor shall be controlled in a level below a certain prescribed limit not to induce thermal stratifications in the flow channels of RCS;
- The cumulative stresses which are to be generated by the load changes of and given to K-DEMO reactor shall not exceed certain prescribed limits that are to be determined on the way of designing the reactor.

Further, to restrict the cumulative stresses to the reactor components not to exceed the allowable stresses, the normal operation of K-DEMO reactor will not be substantially deviated from the following operating specifications:

- The ramp-up and ramp-down rates from HZP to HFP will be within the range of 5-10% of the rated full power per minutes;
- The required time for heating-up and cooling-down will be at least more than couple of hours not to give excessive stresses to the reactor;
- The timespan that K-DEMO reactor will be sustained at HSB and HZP conditions will not be determined by the instability of fusion plasma but by the operator.

As it will take more than 5 hours to ascend and descend from HZP to HFP and from HFP to HZP, the long pulse operation will not be considered in developing K-DEMO.

2.3 Expected achievements of the fusion devices

The achievement of the fusion experimental devices either under operation, construction, or conceptualization are shown in Fig. 1 and expected as follows:

- The advanced tokamaks, including KSTAR, EAST and JT60SA, are expected to achieve HSB condition and give some insight into HZP condition;
- ITER, of which operating target will be less than one hour, will be used for the verification and validation of the reactor physics of HZP condition. It will also generate the experimental data required for the development of the kinetics and control model for K-DEMO. However, the reactor kinetics and control model for the steady state operation of K-DEMO at HFP is not to be developed in ITER due to its operating target of 400 seconds;
- For the Pilot Plant and 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.

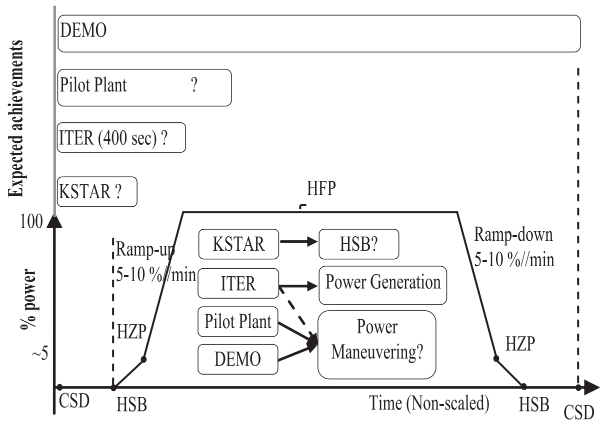

Fig. 1 Expected achievement of the experimental devices.

The design, fabrication, and testing of the blanket and diverter are to be important to the realization of MFE. The materials are to be also significant for the success of K-DEMO program. However, for the development of the first-stage K-DEMO (K-DEMO1) of which the postulated design parameters are shown in Table 1, the materials and testing of the components are to be less significant than the kinetics and control of K-DEMO reactor.

2.4 Nested logic dilemma

As the DEMO reactor will be a first-of-a-kind and its operating parameters are to be too unexceptional to achieve with conventional methods, there will be a logic dilemma of "Whichever is to come first the DEMO reactor or exhaustive test of in-vessel components?": Without the DEMO reactor, the components will not be verified and validated to the exhaustive extent required for the design, building, and licensing of it. To overcome this dilemma, the processes for the development of K-DEMO1 will be as depicted in Fig. 2.

If a failure of structures, systems, and components (SSCs) of a nuclear fusion facility will lead to a release of

Table 1 Design parameters of K-DEMO reactors.

Design Parameters	1st Stage	2nd Stage
Rated power	60 MWe	600 MWe
Availability	~10 %	> 50 %
Fusion power	0.2 GW	2 GW
Major radius	8.14 m	
Minor radius	2.8 m	
Elongation	1.8 (95% flux)	
Tri-angularity	0.35 (95% flux)	
Plasma current	9 MA	21 MA
Fusion gain	> 13.5	> 30
Normalized beta	≥ 4	≥ 4
Magnetic field	6 T	6T
Average neutron wall load	0.2MW/m^2	2MW/m^2
Divertor peak heat load	1MW/m^2	10MW/m^2
RCS* temperature T_{in}(℃) / T_{out}(℃)	290 / 330	TBD
Reactor coolant	Pressurized water / Sub-cooled	
Thermal cycle	Rankine/ Saturated Steam	TBD
Postulated irradiation damage	~ 4 dpa	~200 dpa

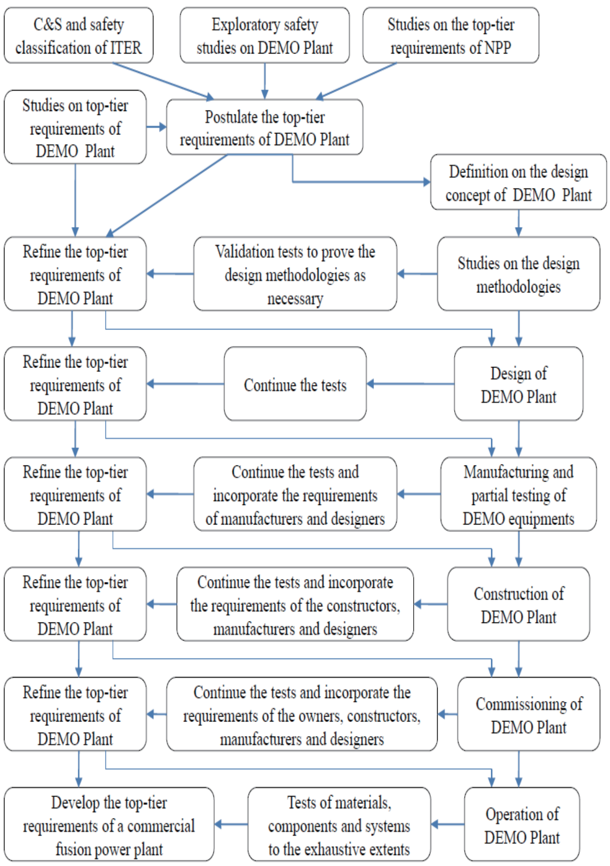

Fig. 2 Proposed Design Processes for K-DEMO1.

a few grams of tritium to the environment these SSCs shall be designed, fabricated, and licensed in accordance with the safety class 2 of the nuclear regulatory requirements of Korea [7]. Therefore, in the case that a design basis event in FNSF and Pilot Plant will lead to the release of the same amount of tritium to the environment, this logic dilemma will be also applicable to the design and construction of these research facilities.

3. Operating Definition of the Staged K-DEMOs

To overcome the nested logic dilemma, the staged development and licensing were proposed in K-DEMO program. K-DEMO1, of which the availability and the power level are postulated to be 10% and 10% of the rated full power respectively will be to verify the technical feasibility focused on the verification and validation (V&V) of the kinetics and control of K-DEMO reactor. The tests of materials and in-vessel components, to the exhaustive extent required for the permit of increasing the reactor power to the rated full power, will be also carried out in this stage.

While developing, construction, and operating K-DEMO1, there will be enhancement in material science, plasma physics, and design of components and systems of K-DEMO-reactor. These improvements are expected to be driven by the research outcomes of the advanced tokamaks including EAST and KSTAR, IFMIF, FNSF, Pilot Plant, and K-DEMO1 itself. The design and materials of the K-DEMO1 reactor will be improved to develop the systems and components of K-DEMO2 reactor, as the comparison is given in Table 1, incorporating the enhancement driven by the aforementioned fusion experimental test facilities. An advanced design that is to be obtained by incorporating the operating data of K-DEMO1 and new development of the fusion materials is to be implemented at this operating outage. With the remote handling mechanisms to be developed, the internal components and systems of K-DEMO1will be replaced to generate the rated full power with enhanced availability to verify the economic feasibility of MFE. The operating outage for the upgrade to K-DEMO2 is to be the most opportune time to test and develop the overhaul maintenance of the fusion reactor. The design parameters estimated with the results of zero dimensional analysis using a system code [8] and major milestones of the staged K-DEMO are to be as shown in Table 2.

4. Near-Term Cross-Cuttings

4.1 Pathway and timelines to K-DEMO1

The pathway to K-DEMO1, shown in Fig. 3, will be as follows:

- In DEMO Preparatory Program, from 2009 through 2011, the strategic plan for DEMO Program and implementation plans for the sub-programs will have been developed and front-end R&D activities will have been carried out to expedite the DEMO development;
- In DEMO R&D Program, from 2012 through 2021,

Table 2 Major Milestones of K-DEMO Program.

Milestone	Year
Define K-DEMO and establish pathways	2014
Design study for K-DEMO plant	2018
K-DEMO1 FEED and site selection	2021
Construction permit for K-DEMO1	2022
ITER D-T operation to be started	*2027*
Material selection for K-DEMO2	2030
Complete construction of K-DEMO1	2035
Prove the technical feasibility of MFE	2036
Construction permit of K-DEMO2	2037
Prove the economic feasibility of MFE	204x

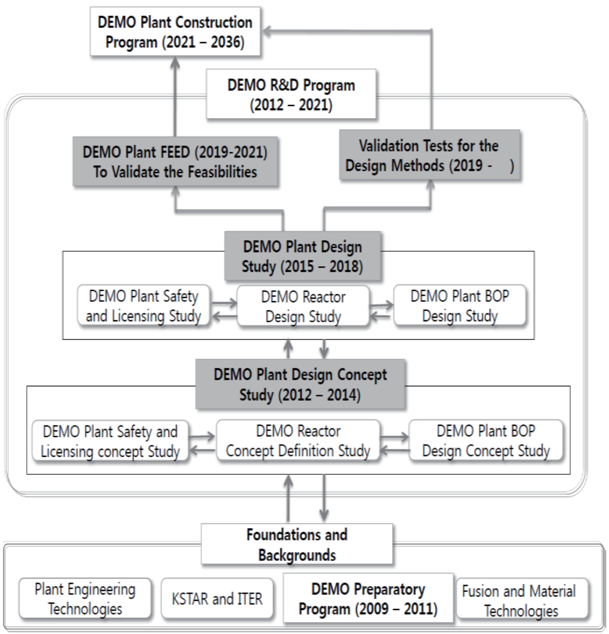

Fig. 3 Rough roadmap for K-DEMO1.

the design studies for K-DEMO1 will be carried out to develop engineering and construction technologies required to build it, and FEED (Front End Engineering Design) of K-DEMO1 will be conducted to validate its economic and technical feasibilities;

- In DEMO Construction Program from 2022 through the 2036, the first-stage DEMO Plant will be designed, constructed, commissioned and operated to demonstrate electricity generation.

The investment to the DEMO preparatory program was 5 million US$. The investments to DEMO R&D program and DEMO construction program are forecasted to be 500 million and 4.5-10.5 billion in 2009 US$ respectively.

The major milestones of K-DEMO program are shown in Table 2. However, the recent changes in schedule baseline of ITER and potential delay due to the earth quake in Japan have not been incorporated in the milestones.

As also shown in Fig. 2, DEMO R&D program is further divided into three sub-programs: K-DEMO1 Design Concept Study from 2012 through 2014, K-DEMO1 Design Study from 2015 through 2018, and K-DEMO1 FEED at the same time with validation tests for design methods of K-DEMO1 from 2019 through 2021.

4.2 Near-term cross-cutting ideas

The near-term cross-cutting ideas with the technologies and research works of the existing nuclear power plants (NPPs) may include the following areas:

- The top-tier requirements for K-DEMO1 may use that for the existing NPPs, including the general design criteria, regulatory guides, safety classifications and quality assurance, with some modifications based on reasonable postulations until a new set of dedicated top-tier requirements are to be developed for K-DEMO1;
- All or part of existing codes and standards including that of ASME (American Society of Mechanical Engineers) and IEEE (Institute of Electrical and Electronics Engineers) are to be used for the design studies for K-DEMO1 until the codes and standards dedicated to DEMO will be developed;
- Computational codes used for the safety analysis, thermo-hydraulic analysis and neutronics analysis of the existing NPPs are to be used for that of K-DEMO1 by extending the validated ranges of the computer codes;
- Irradiation history of the structural materials of the existing NPPs is to be referred to select the materials of K-DEMO1;
- Structural design methods and equipment qualifications will be used for the front-end R&D activities of K-DEMO1;
- The processes for the project management, engineering, procurement, construction and commissioning of NPP are to be modified to establish the life cycle processes of K-DEMO1.

As shown in Fig. 3, the near-term cross-cuttings that have been carried out or planned to implement are to define K-DEMO1 and discover the pathway to K-DEMO1 in accordance with the design methodologies, the codes and standards (C&S), and regulatory requirements of the existing NPPs.

4.3 Cross-cuttings in the preparatory studies

As discussed before, the DEMO Preparatory Program has been carried out from 2009 through 2011. During this period, the preparatory studies on K-DEMO1 have been performed making the best use of the commonalities.

For the selection of the materials, the materials to be used for K-DEMO1 are to be ∼ 4 dpa with the operating

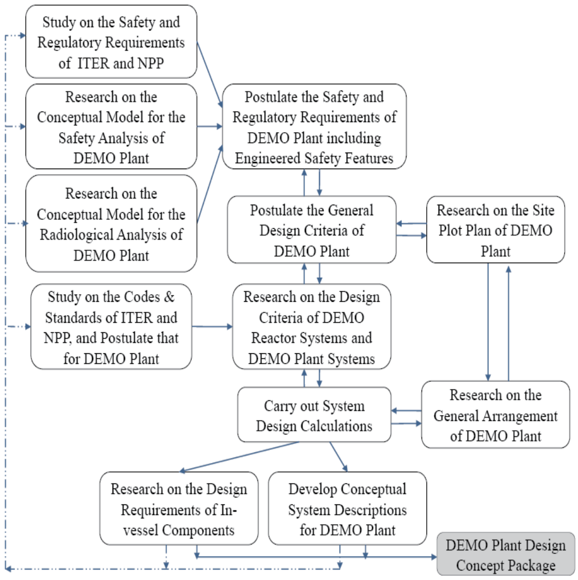

Fig. 4 K-DEMO1 Design Concept Study.

pressure and temperature comparable to that of the current NPPs of which the type is a pressurized water reactor as shown in Table 1. Reviews on the irradiation history of the structural materials of the existing NPPs [9, 10] were carried out and the austenitic stainless steel that has been used for the NPPs was selected as a candidate for the structural materials of K-DEMO1 in addition to a reduced activation martensitic ferritic steels and oxide dispersion strengthened ferritic steels.

For the regulatory requirements of K-DEMO1 the general design criteria (GDC) for the NPPs of the US were reviewed to check the adaptability to K-DEMO1 as that of Korea were not fully written in the other languages. The GDC, Appendix A of 10CFR50 of US, shown in Table 3, will be generally applicable with some modifications of GDC 55, 56, 57, 60, 61, 63, and 64 based on the studies of the behaviors of tritium for the design concept studies for K-DEMO1.

For the classifications of the structures, systems, and components (SSCs) of K-DEMO1 were studied in accordance with the following postulated criteria:

- The SSCs of which failure will lead to the radiation releases of exceeding 3.7 GBq shall be classified as Safety Class 2;
- The SSCs of which failure will lead to the release of 370 MBq or will lead to the exposure of exceeding 0.5 rem shall be classified as Safety Class 2.

To determine the classification criteria of K-DEMO1, the system boundaries of K-DEMO1 were defined as follows:

- The vacuum vessel pressure boundary (VVPB) that corresponds to the reactor coolant pressure boundary of the NPPs is defined to be vacuum vessel (VV), fuel systems, reactor coolant systems and piping systems penetrating VV up to and including the first isolation mechanism from VV;
- The reactor containment boundary (RCB) is to be defined as RCB that contains the VVPB and piping systems penetrating RCB up to and including the first isolation mechanism from RCB;
- The engineered safety features (ESFs) are to be the fluid systems that mitigate the failure of the integrity of VVPB and RCB;
- The BOP safety systems are to be the fluid systems that are not permanently connected to VVPB and RCB are to carry out safety related functions under normal, abnormal, and accident conditions;

Table 3 Applicability of GDC of NPP to K-DEMO1.

General Design Criteria	Applicability
1. Quality Standards and Records	Use As Is
2. Design Based for Protection Against Natural Phenomena	
3. *Fire protection*	
4. *Environmental and dynamic effects design bases*	
5. *Sharing of structures, systems, and components*	Not Applicable
10. *Reactor design*	Need Modification
11. *Reactor inherent protection*	Not Applicable
12. *Suppression of reactor power oscillations*	Need Modification
13. *Instrumentation and control*	
14. *Reactor coolant pressure boundary*	
15. *Reactor coolant system design*	
16. *Containment design*	Use As Is
17. *Electric power systems*	
18. *Inspection and testing of electric power systems*	
19. *Control room*	
III. Protection and Reactivity Control System (GDC 20 through GDC 29)	Not Applicable
30. *Quality of reactor coolant pressure boundary*	Need Modification
31. *Fracture prevention of reactor coolant pressure boundary*	Need Modification
32. *Inspection of reactor coolant pressure boundary*	Need Modification
33. *Reactor coolant makeup*	Use As Is
GDC 34 through 40	Not Applicable
41. *Containment atmosphere cleanup*	Use As Is
42. *Inspection of containment atmosphere cleanup systems*	Not Required for the Studies of the Design Concept of DEMO
43. *Testing of containment atmosphere cleanup systems*	
44. *Cooling water*	
45. *Inspection of cooling water system*	
46. *Testing of cooling water system*	
50. *Containment design basis*	Need Modification
51. *Fracture prevention of containment pressure boundary*	Not Required for the Studies of the Design Concept of DEMO
52. *Capability for containment leakage rate testing*	
53. *Provisions for containment testing and inspection*	
54. *Piping systems penetrating containment*	Use As Is
55. *Reactor coolant pressure boundary penetrating containment*	Need Modification
56. *Primary containment isolation*	Need Modification
57. *Closed system isolation valves*	Need Modification
60. *Control of releases of radioactive materials to the environment*	Need Modification
61. *Fuel storage and handling and radioactivity control*	
62. *Prevention of criticality in fuel storage and handling*	Not Applicable
63. *Monitoring fuel and waste storage*	Need Modification
64. *Monitoring radioactivity releases*	

- The safety related I&C and electrical systems are to control the functions of the safety-related systems and supply the electric power to the safety-related systems.

To determine the classification of K-DEMO1, with the safety analysis methods and computation codes of the NPPs, the radiation release after the postulated events were estimated as follows:

- An in-vessel loss-of-coolant accident with the failure of VVPB and RCB is to lead to a release of radio-activity greater than 37 GBq;
- In the event of an ex-vessel rupture of a piping component in the tritium systems, with the failure of RCB, the radio-activity release after the event is to be greater than 37 GBq;
- The failure of BOP safety-related systems will lead to the radio-activity release that is to be greater than 370 MBq but less than 37 GBq;
- The failure of ESF is to lead to a release of radio-activity greater than 37 GBq.

The safety classification of SSCs of K-DEMO 1 is to be defined as summarized in Table 4, if that of the NPPs will be applied with the aforementioned system boundaries and the radio-activity release after a postulated event in K-DEMO1.

For the design, material selection, manufacturing and testing of SSCs of DEMO Plant C&S applicable for the NPPs will be applicable as long as their safety classification and design parameters are to be compatible with existing C&S.

The C&S applicable for DEMO Plant are to include, but not limited to, ASME, API (American Petroleum Institute), NFPA (National Fire Protection Association), ACI (American Concrete Institute), ANSI (American National Standard Institute), ASTM (American Society of Testing Materials), ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers), AWS (American Welding Society), and IEEE.

However, as the current C&S are not sufficient to design, test and build the components that are Safety-Related or unique to DEMO Plant, at least, the studies on the C&S should be carried out on the following areas:

Table 4 Classification of K-DEMO1 SSCs.

SSCs	Proposed Classification Criteria
Systems and Components of VVPB	Quality Group B, Seismic Category I
Systems and Components of RCB	Quality Group B, Seismic Category I
Engineered Safety Features (Fluid systems)	Quality Group B, Seismic Category I
Safety Related Electrical and I&C Components	Class 1E, Seismic Category I
BOP Safety-Related Systems	Quality Group C, Seismic Category I
In Vessel Components	Quality Group B, Seismic Category I

- Design, selection and testing of materials, fabrication and testing of the components specific to DEMO including VV, super-conductor magnets, piping systems and storage equipment for tritium, blanket, and diverter;
- Commissioning and in-service inspection requirements for the super-conductor magnets, cryogenic components and system, and vacuum components and system;
- In-service inspection methods and requirements for the double-wall VV.

4.4 Benefits of near-term cross-cuttings

Design of a power plant that is to have a potential of radiation release shall be carried out in accordance with the top-tier requirements including the regulatory requirements and C&S applicable for the design, material selection, testing, installation, and commissioning of the plant. As depicted in Fig. 1, that for K-DEMO1 will not be fully developed until it will be commissioned and operated. The design methodologies and computational codes of the NPPs are to be used with some modifications and extensions with additional studies required for these purposes. Irradiation history and researches of the structural materials of the NPPs are to be utilized for the selections of the materials for K-DEMO1. These cross-cuttings will lead to the reductions of the investment to the design concept studies on K-DEMO1 and expediting the studies. A way to break through the nested logic dilemma is to be discovered with the cross-cutting with the NPPs. The risks associated with developing K-DEMO1 are to be mitigated with the cross-cuttings as well.

5. Mid- to Long-Term Cross-Cuttings

5.1 Sharing of the test facilities of the NPPs

To develop K-DEMO1, new test facilities including the remote handling test facility, magnet test facilities, and heating and current drive test facilities dedicated to K-DEMO1 will be identified and constructed to test the design methods and materials. However, the investments to design, construct, and operate these test facilities and the risks associated with investment to these test facilities will be significant. To mitigate the risks the R&D facilities of the NPPs, shown in Table 5, that are HANARO (High flux Advanced Neutron Application Reactor) ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simu-

Table 5 Use of the existing nuclear test facilities.

Test facilities	Areas of study
HANARO	Irradiation damage of 4dpa with thermal neutrons
WTRF	Tritium behaviors in the piping systems
ATLAS	- V&V of T-H codes - Flow model tests - V&V of safety analysis

lation), and WTRF (Wolsong Tritium Removal Facility) will be used to test the materials and design methodologies for K-DEMO1.

5.2 Cross-cutting with Gen. IV NPPs

As many authors have discussed [11–15], K-DEMO1 will make the best use of the research outcomes of Gen. IV NPPs including, but not limited to, the structural materials, heat transfer technologies, design of thermal cycles, radiation protections, and I&C mechanisms

5.3 Tritium supply

It is postulated that the tritium inventory required for the initial operation of K-DEMO1 will be supplied from WTRF. It is further postulated that tritium will be self-sufficient in K-DEMO1.

6. Conclusion

Studies on DEMO could be benefited from the cross-cuttings that are to make the best use of the commonalities with the existing and GenIV NPPs as the investment to the DEMO could be cut down and the timelines for DEMO could be expedited. With these cross-cuttings the risk associated with developing DEMO could also be mitigated.

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