On Korean Strategy and Plan for Fusion Energy

Hyuck Jong Kim[1], Won-jae Choi[2], Changwoo Park[3], Hyung Chan Kim[1]
[1] National Fusion Research Institute, Daejeon, the Republic of Korea
[2] Chungnam National University, Daejeon, the Republic of Korea
[3] POSTECH, Pohang, the Republic of Korea

Abstract

In developing KSTAR (Korean Superconducting Tokamak Advanced Research), Korea had initiated a mid-entry strategy to catch up with the technologies required for the development of a fusion reactor, based on the tokamak magnetic confinement concept. Upon joining ITER (International Thermonuclear Experimental Reactor), Korean government enacted a promotional law for the fusion energy development. Under this promotional law the national promotional plans for developing fusion energy have been established. The National Fusion Research Institute (NFRI) developed the strategy and plan for a fusion DEMO program to realize the magnetic fusion energy.

1. Background

1.1 Before KSTAR (Korean Superconducting Tokamak Advanced Research)

The history of Korean nuclear fusion research and development (R&D) began with SNUT-79 (Seoul National University Tokamak–79) which was developed from 1979 through 1989 by the faculties, staff, and students of the Nuclear Engineering Department, College of Engineering, Seoul National University. KAERI (The Korean Atomic Energy Research Institute) and KAIST (The Korean Academy and Institute of Science and Technology) started operation of KT-1 (KAERI Tokamak-1) and KAIST-Tokamak respectively in 1994. The latter was a re-assembly of PRETEXT device obtained from the University of the Texas at Austin of US, transferred to KAIST. Information on these tokamak devices and their position in the history of nuclear fusion R&D are shown in Table 1 and Figure 1 respectively.

1.2 Platform KSTAR and mid-entry strategy

In 1995, the Korean government established national R&D plans for nuclear fusion technologies and set up the mid-entry strategy, shown in Figure 1, to develop and make the best use of KSTAR to catch up with the technologies required for the realization of magnetic fusion energy (MFE) using the tokamak concept. Development of the platform of KSTAR was started in 1995 and completed in 2007. The first plasma in KSTAR was achieved in June 2008. Since 2007, KSTAR has been evolving.

For the development of KSTAR, in addition to the researchers, engineers, and administrator of NFRI, 1,510 participants from 69 Korean domestic companies collaborated in developing KSTAR. The global collaboration with the research institutes of the world and governmental collaboration were also the critical success factors for KSTAR.

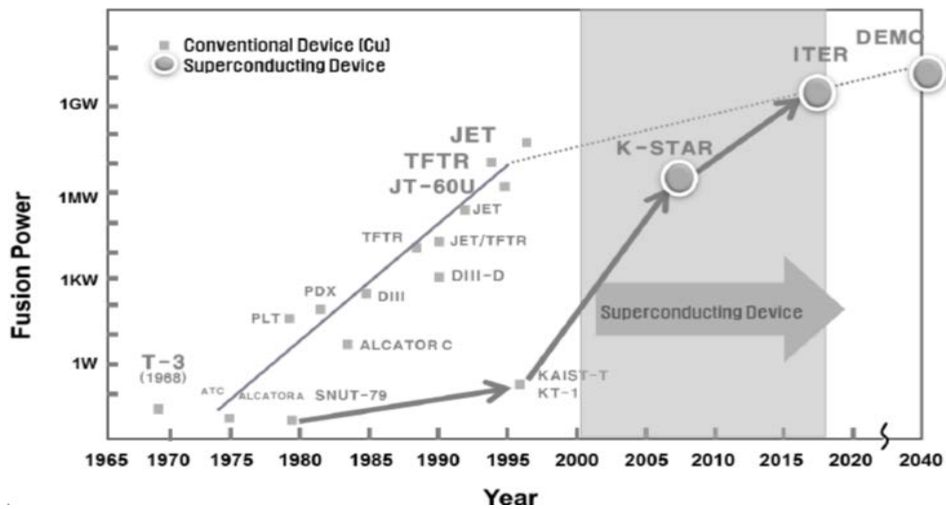

Figure 1: Mid-entry Strategy.

Table 1: Brief description of the tokamaks in Figure 1

Name (Full Nmae)	Country	Institute	Operation	Major Radius (m)	Minor Radius (m)	TF (tesla)	IP (MA)
ALCATOR C (Alto Campo TORus C-Mod)	USA	MIT	1993	0.67	0.22	8	2
ASDEX upgrade (Axially Symmetric Divertor)	Germany	IPP	1991	1.65	0.5-0.8	3.9	1.4
DIII-D	USA	GA	1986	1.66	0.67	2.2	3
EAST (Experimental Advanced Superconducting Tokamak)	China	CASS (Hefei)	2006	1.75	0.43	5 SC	0.5
ITER	France	IO (Cadarache)	2020	6.20	2.00	5.3 SC	17
JET (Joint European Torus)	EU	Culham	1983	2.96	0.96	4	6
JT-60SA	Japan	JAEA (NAKA)	2014	3.16	1.02	2.7 SC	5.5
KAIST	Korea	KAIST (Daejeon)	1992-2002	0.53	0.14	0.5	0.12
KSTAR	Korea	NFRI (Deajeon)	2008	1.80	0.50	3.5 SC	2
SNUT-79	Korea	SNU	1982-1992	0.65	0.15	0.08	0.006
T-3	USSR	Kurchatov	1960-1971	1.00	0.12	4	0.06
TFTR (Tokamak Fusion Test Reactor)	USA	PPPL	1982-1997	2.40	0.80	6	3

1.3 Joining ITER and legislating the Act of Promoting Fusion Energy Development

One of the unique and strategic strengths of the fusion research program of Korea is that it has a dedicated law. As the activities and investments for fusion energy development of Korea had increased significantly over time, the need for a dedicated law was identified. Thus, the Act of Promoting Fusion Energy Development was legislated in 2007 to promote investments, to increase the availability of human resources, to define the promotional and administrative activities of the government, to control the governmental budget more efficiently and effectively, and finally, to construct the research facilities for that purpose.

1.4 National Plans for the Development of Fusion Energy

In accordance with the aforementioned act, the Ministry of Education and Science and Technology (MEST) developed and publicized the national promotion plan for the development of fusion energy for every five-year starting from 2007. MEST also established the annual implementation plan for the fusion energy development in line with the 5-year national plan.

The Master Promotion Plan of 2007, effective until 2011, was developed with vision of developing fusion energy to secure it as long-term sustainable energy resource and the final goal of realizing electricity generation with MFE by 2036. The National Fusion Research Institute (NFRI) that is a governmental institute, dedicated to the fusion energy development, developed the strategy and plan for a Korean fusion program based on the DEMO successor to ITER (K-DEMO), and is trying to discover the gaps and pathways to the realization of the magnetic fusion energy. At the end of 2011, Korean government established and publicized the promotion plan effective from 2012 through 2016: While maintaining the underlying polices of the Plan of 2007, the front-end activity of K-DEMO program was newly introduced in the new national plan.

1.5 KSTAR in 2011

KSTAR is a superconducting tokamak of which both the system specifications and experimental accomplishments are still evolving in comparison with its platform constructed in 2007 as they are shown in Table 2 and Figure 3 respectively.

Table 2: Evolution of KSTAR

Systems \ Year	2007	2008	2009	2010	2011
H&CD systems	-	1.5	2.2	3.2	3.5
Cryogenic systems(㎾)	-	9	9	9	9
PFC coverage(㎡)	-	1.54	11.08	52.94	-

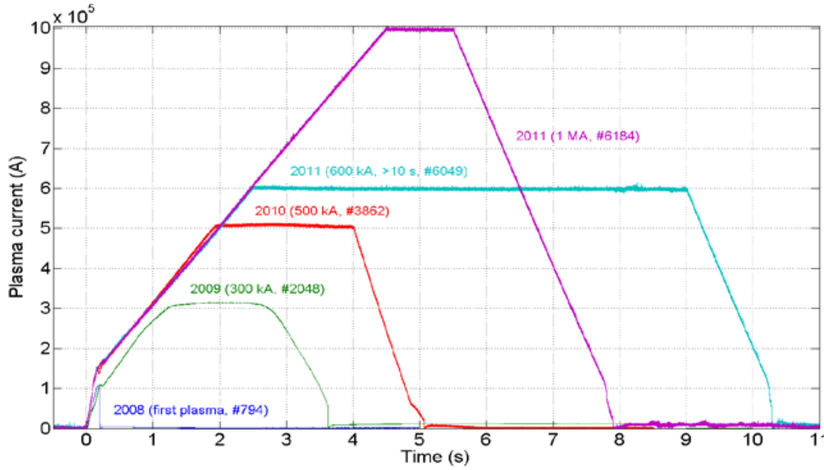

Figure 2: Evolution of KSTAR Experiments

2. The strategic plan for K-DEMO program

2.1 Processes for developing the strategic plan

As the processes are shown in Figure 3, the strategic plans of the K-DEMO program were developed adopting the SWOT (Strengths, Weaknesses, Opportunities and Threats) and SCAN (Strategic Creative Analysis) that are generally applicable for the development of strategic plans.

Figure 3: Processes Used for Developing the K-DEMO Strategic Plan

2.2 Vision, mission, and strategic goal

The vision of K-DEMO program is "*The great journey from KSTAR, ITER, to DEMO to be an early demonstrator of fusion energy*" [1]. The mission statement of the program is "*The* *participants would succeed the inherited pioneering spirits of fusion energy development and make the best use of KSTAR and ITER to innovate the practical way of realizing sustainable energy resource*" [1]. The strategic goal of K-DEMO program is realizing electricity generation with MFE in 2036 to develop the first commercial fusion power plant in the 2040s: this strategic goal is under review considering the changes in the program environments including the new baselines of ITER [1].

2.3 Key strategies, strategic initiatives, and implementing measures

The key strategies of K-DEMO program derived from SWOT analysis and MPA (matched pair analysis) are as follows [1]:

- Being an early mover (SO Strategy) to take advantages of the opportunities in the future energy market;
- Enhancing international collaboration (SWT Strategy) to make efficient use of the limited resources through synergetic collaboration with the other countries and respond to global competition in developing the fusion science and technologies;
- Adopting an open innovation strategy (WO Strategy) including global collaborations to make the best use of the investment to fusion energy;
- Promoting science businesses (WT Strategy) to enhance credibility of K-DEMO program and public acceptance as well.

The strategic initiatives and implementing measures corresponding to the key strategies of the program are summarized in Table 4 [1]. To mitigate the risks associated with the early mover strategy, the measures considered in the strategic plan of K-DEMO program are as follows:

- The design of K-DEMO plant will be carried out making the best use of the information technologies (IT) including 3D CAD, computational fluid dynamics and magneto-hydro-dynamics, virtual reality, and design automation until kinetics and control model for K-DEMO reactor will be developed. With these IT-based engineering works, the total investment until 2027, when the D-T operation of ITER will be started, will be less than 1% of the total estimated cost of K-DEMO program;
- Cross cutting with NPPs to make the best use of the commonalities between fusion and fission [2-4] will be extensively considered including sharing of the test facilities for verification and validation (V&V) of the various computational simulation and modeling codes that are to be used for the design and operational analysis of K-DEMO reactor;

- Technical and economic feasibilities will be verified and validated by carrying out FEED (front end engineering and design) before starting the basic design of K-DEMO1.

Table 3: Implementing Measures

Strategic Initiatives	Implementing Measures
To be an early mover: K-DEMO1 design in parallel with KSTAR and ITER, and staged licensing of KDEMO1	• Make the best use of the engineering technologies and test facilities of the nuclear power plants to cross-cut the front-end design activities of K-DEMO1; • Mitigate the risks associated with the design of K-DEMO1 in parallel with the development of science and technologies required for the realization of MFE; • Prove the inherent safety of K-DEMO1 for the staged licensing and get the early involvement of the licensing authority.
To enhance international collaboration: Increases in the promotional activities to	• Make the best use of KSTAR as a platform device for the global fusion research; • Form a multi-national DEMO Program;
To carry out open innovation strategy: Cross cutting with existing systems and open innovation in the global contexts	• Make the best use of the resources and technologies in the domestic and global contexts to facilitate R&D portfolio management and cross-cutting ideas; • Operate VR, ubiquitous, real-time Fusion DEMO Research Center.
To Promote Science Business: Deploy strategic science business activities with the interim R&D deliverables of DEMO design study	• Share the research plan with the industries to discover the interim deliverables that may meet the demand of the industries; • Deploy strategic co-research projects with the plant industries with the interim deliverables.

2.4 Staged K-DEMO Program and Phased K-DEMO1 Program

To overcome the most significant gap and nested logic dilemma, the staged development and licensing were proposed in K-DEMO program [5]. The first-stage K-DEMO (K-DEMO1) will verify the technical feasibility focused on the verification and validation (V&V) of the kinetics and control of K-DEMO reactor with reduced power. The tests of materials and in-vessel components, to the exhaustive extent required for the operation permit of increasing the reactor power to the rated full power, will be also carried out in this stage. While developing, constructing, and operating K-DEMO1, there will be enhancement in material science, plasma physics, and design of components and systems of MFE reactors. These enhancements that will be incorporated in the design of the second-stage K-DEMO (K-DEMO2) are expected to be driven by the research outcomes of the advanced tokamaks including EAST and KSTAR, IFMIF, FNSF (Fusion nuclear science facility) [6], Pilot Plant (PP) [7], and K-DEMO1 itself. After verifying the technical feasibility of MFE, the internal components and systems of K-DEMO1will be replaced with that of advance design to build the second-stage K-DEMO (K-

DEMO2) to generate the rated full power with enhanced availability to verify the economic feasibility of MFE. The design parameters of K-DEMOs, estimated with the zero dimensional analysis using a system code [8], are compared in Table 4.

Table 4: 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	6 T
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 / Sub-cooled	
Thermal cycle	Rankine/ Saturated Steam	TBD
Postulated irradiation damage	~ 4 dpa	~200 dpa

K-DEMO1 program will be carried out with the three phased programs, shown in Figure 4, to mitigate the risks associated with developing MFE as follows [1, 3]:

- Phase I was DEMO preparatory program and started in 2009 and will end in 2011. In this phase the strategic plan for K-DEMO program was developed and the front-end R&D activities required for the development of the strategic plan were carried out;

- Phase II is DEMO R&D program, from 2012 through 2021. Pre-conceptual design of K-DEMO plant will be carried out not to design K-DEMO, but to discover engineering and construction technologies that should be developed to realize MFE. At the end of DEMO R&D program, FEED (Front End Engineering Design) for K-DEMO will be performed to verify its economic and technical feasibilities before starting the construction to mitigate the risks associated with the investment to K-DEMO;

- In Phase III, from 2022, the 1st stage K-DEMO will be designed and constructed to realize MFE in 2036.

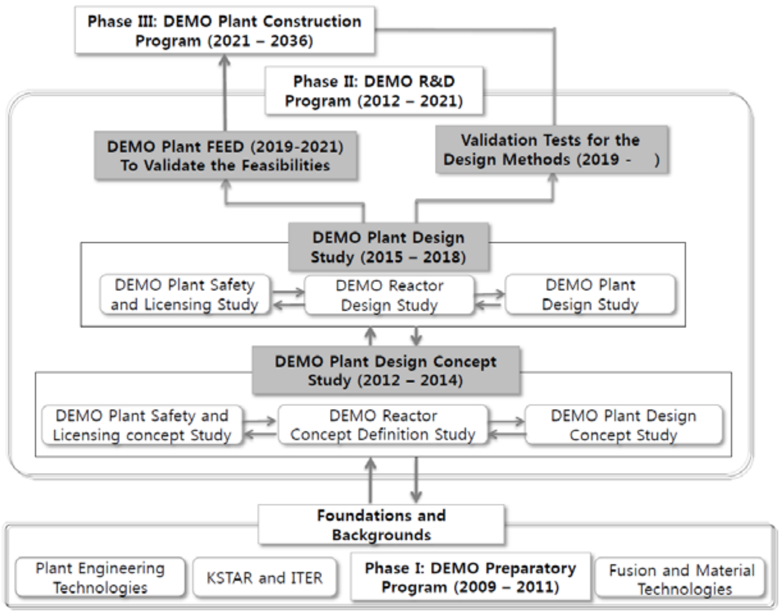

Figure 4: Overview of K-DEMO1 Program

The investments to the DEMO preparatory program, DEMO R&D program and DEMO construction program are forecasted to be 5 million US$, 500 million and 4.5 – 10.5 billion in 2009 US$ respectively [1]. As the science and technologies required for the development of MFE are expected to be immature at least until the end of this decade risks associated with investment to MFE should be considered in K-DEMO program. The major milestones of K-DEMO program and forecasted investment profile are shown in Table 5 and figure 6 respectively. However, the recent changes in the schedule baseline of ITER and potential delay due to the earthquake in Japan will be incorporated in the milestones after carrying out details studies on the subject delays.

Table 5: Major Milestones of K-DEMO Program

Phase	Milestone	Year
II	Define K-DEMO and establish a pathway	2014
II	Design study for K-DEMO plant	2018
II	DEMO FEED and site selection	2021
III	Construction permit for the 1^{st} phase K-DEMO	2022
III	*ITER D-T operation to be started*	*2027*
III	Material selection for the 2^{nd} stage K-DEMO	2030
III	Complete construction of the 1^{st} phase	2035
III	Prove the technical feasibility of MFE	2036
(2^{nd} stage)	Construction permit of the 2^{nd} stage K-DEMO	2037
	Prove the economic feasibility of MFE	204x

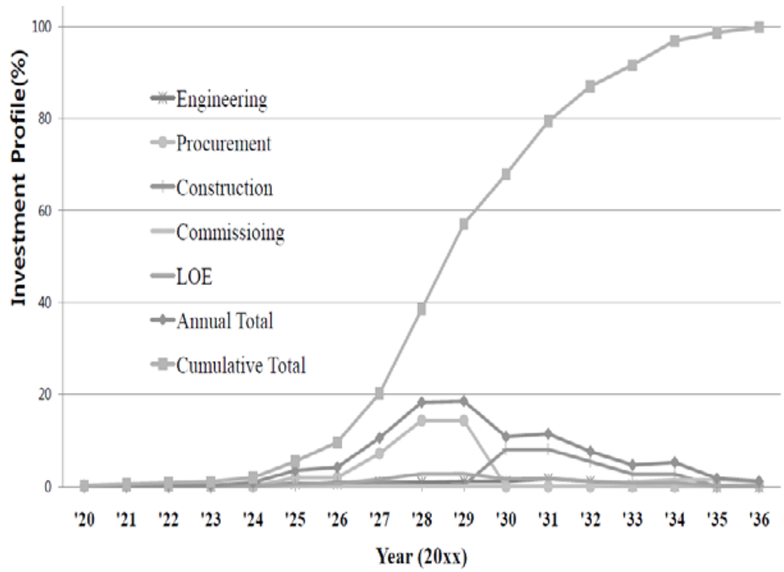

Figure 5: Forecasted Investment Profile for DEMO Construction

3. Implementation Plan for K-DEMO R&D Program

3.1 Processes for Developing the Implementation plan

As Phase II DEMO R&D program will be started from 2012 an implementation plan for this phase is further developed in accordance with the integrated planning model shown in Figure 6. To form this model, the most commonly used business management and project management skills including gap study, strategic management, scope management including WBS (Work Breakdown Structure) and project frame chart, project prioritization, and project risk management were applied and combined.

3.2 Implementation Plan for Phase II

The R&D program is further divided into the three phases, as it is shown in Figure 4, also to mitigate the risks associated with developing MFE in parallel with developing science and technology for that purpose. In this phase, the total governmental investment and cumulative manpower on the R&D activities are estimated to be around 400 million in 2009 US$ and 2,200 Man-years, respectively, not including those of the industries. The number of NFRI staff at the peak of this phase is estimated to be 420 [2]. The cash flow projections of Phase II are shown in Figure 7 and the list of the R&D facilities with the forecasted capital investments is shown in Table 6 [2]. The R&D activities that will be carried out in each phase of R&D program shown in Figure 4 are described in Table 7 [2].

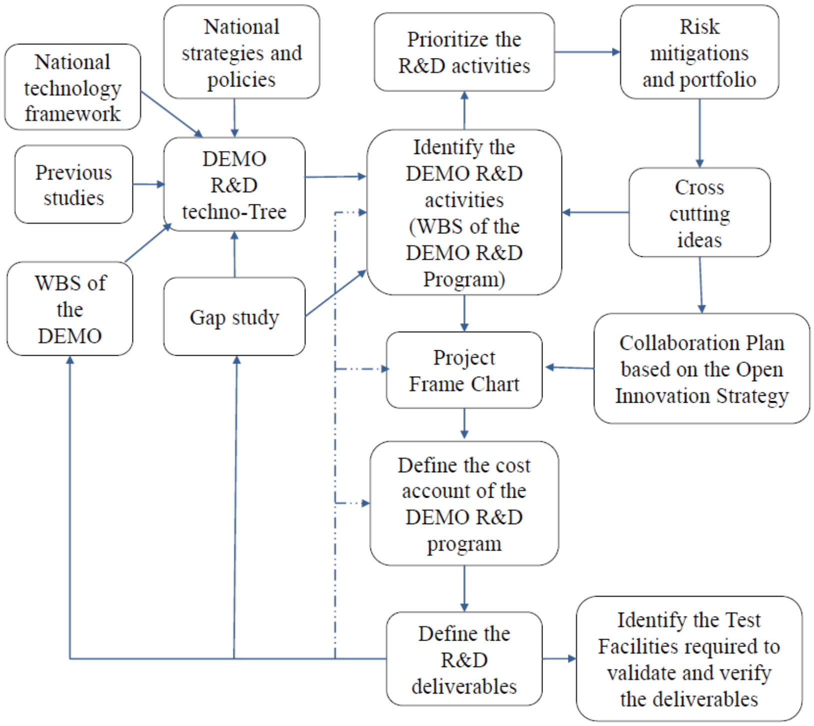

Figure 6: Processes for Developing the Implementation Plan for the K-DEMO Program

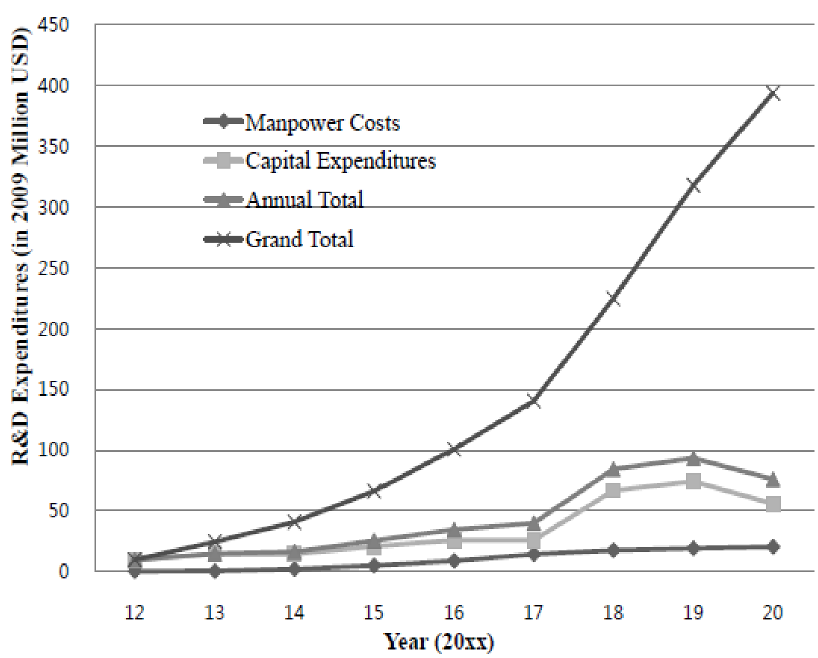

Figure 7: Forecasted Capital Expenditures for Phase II

Table 6: List of R&D Test Facilities of Phase II

R&D Facility Description	Building Area (m^2)	Forecasted Costs (mill US $)
Front-end R&D and DEMO Plant Design Study Center, Fusion Plasma Simulation Center, Fusion Material Testing Center, Business Science Incubating Center	7,600	65
Superconducting Magnet R&D Center, H&CD R&D Center and Fuel Cycle R&D Center	9,800	150
Reactor I&C R&D Center, Remote Handling R&D Center, Science Business Center, and T-H R&D and Validation Test Facility	15,100	135
Total	32,500	350

Table 7: R&D Activities of Phase II

Period	Research Objectives	Research Activity Description
2012 – 2014	K-DEMO1 Design Concept Study	- DEMO reactor design concept study includes the studies on the DEMO concept definition, blanket design concepts, diverter design concepts, reactor coolant system (RCS) and reactor fuel system design concept, fusion material functional specifications; - DEMO plant design concept study includes the studies on the layout concept, thermal cycle concept, system design concept, cost/schedule/risk evaluation model; - DEMO plant safety and licensing concept study includes the studies on the concepts of the fusion DEMO regulatory requirements, conceptual models for safety analysis and radiological analysis, inherent safety study, concepts of engineered safety features.
2015 – 2018	K-DEMO1 Design Study	- DEMO reactor design study includes the studies on the reactor kinetics and control model, DEMO reactor instrumentation and control, RCS and fuel system design, design of validation test facilities, adaptability and manufacturability of materials, engineering prototyping of the blanket and diverter for the T-H tests; - Demo plant design study includes the studies on the layout optimization, thermal cycle optimization, automation of construction, automation of operation and maintenance, evaluation model for the economic feasibility of MFE; - DEMO plant safety and licensing study includes the studies on the draft regulatory requirements, validation of inherent safety, in-service and pre-service inspection requirements.
2019 – 2021	K-DEMO1 FEED & validation tests	- DEMO reactor conceptual design and validation tests - DEMO FEED to validate the technical and economic feasibilities

4. Conclusion

NFRI developed the strategic plan of K-DEMO program aiming at the realization of MFE by 2036 and the Korean government included the front-end R&D activities of the strategic plan in the national promotion plan for the development energy. However, this target will be revised incorporating the new timelines of ITER.

5. Acknowledgement

The authors sincerely appreciate the researchers of the KSTAR Division of NFRI for providing the status and history of the KSTAR experiment. The authors also sincerely appreciate Drs. Y. Lee, HS. Chang, HS. Do, and JH. Yeom of NFRI for their contribution to the development of the national strategy for the fusion energy development.

6. References

[1] HJ. Kim, HC. Kim, Chul-Sik Lee, M. Kwon, and GS. Lee "The strategic plans for the fusion DEMO program of Korea", Transactions of Fusion Science and Technology, Vol. 60, Iss. 2, 2011, pp. 433-440.

[2] L. El-Guebaly, L. Cadwallder, W. Sowder and the ARIES Team, "Challenges of fusion power plant licensing: Differences and commonalities with existing systems", Proceedings of TOFE 19, Transactions of Fusion Science and Technology, Vol. 60, Iss. 2, 2011, pp. 751-759

[3] J. Cho, G. Heo, Y. Lee, and HJ. Kim, "Comparison study on the safety characteristics of fission and fusion power plants in Korea", Proceedings of TOFE 19, Transactions of Fusion Science and Technology, Vol. 60, Iss.1, 2011, pp. 1-8.

[4] F. Li, V. Barabash, W. Curd, G. Dell'Orco, B. Gopalapillai, KP. Chang, S. Ployhar, and F. Somboli, "Classification of ITER tokamak cooling water system in accordancec with French regulations concerning nuclear and pressure equipment", Proceedings of TOFE 19, Transactions of Fusion Science and Technology, Vol. 60, Iss. 2, 2011, pp. 781-785.

[5] HJ. Kim, G. Heo, JK.Kim, HC. Kim, M. Kwon, and GS. Lee, "Fusion DEMO Program of Korea; Overview and DEMO R&D Plans", Transactions of Fusion Science and Technology, Vol. 61, Iss. 1t, 2012, pp.21-27.

[6] M. Peng et al., "Fusion Nuclear Science Facility (FNSF) before Upgrade to Component Test Facility (CTF)", Fusion Science and Technology, Vol. 60, Iss. 2, 2011, pp.441-448.

[7] H. Neilson, "Pilot Plant Options for Magnetic Fusion Development", 15th International Conference on Emerging Nuclear Energy (ICENES-2011), San Francisco, USA, 2011 May 15-19.

[8] S.W. Haney et al., "A SUPERCODE for Systems Analysis of Tokamak Experiments and Reactors", Fusion Technology, Vol. 21, 1992, p. 1749.