Lessons Learned from KSTAR Construction and Commissioning

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KSTAR is an advanced tokamak with fully superconducting coils for the steady state research, which began in December 1995 and was completed in July 2008. As a single science project, it has been marked as the largest construction project in the history of Korea. During the construction period, we encountered several challenges, such as technical issues, cost overrun and schedule slippage. Nevertheless, we managed to overcome the difficulties through the devotion of all the participants under a strong leadership, and we finally succeeded in the first plasma discharge of 133kA/865ms in July 2008. Therefore, KSTAR, the first Nb_3Sn based fully superconducting tokamak, has been recorded as the device that passed its commissioning without failure at its first trial. And as we speak, KSTAR is sustaining its momentum for the next campaign: it is getting ready for its operation of the toroidal magnetic field of 3 Tesla. At this presentation, we focus on the actual applications and resolutions applied to surmount the difficulties we faced during the KSTAR construction, as well as the events that occurred behind the scenes. Despite the scale difference between KSTAR and ITER, we strongly believe that the presentation will provide a great insight to the construction of the ITER device, which is very similar to KSTAR in terms of design and characteristics.

Keywords: tokamak construction, performance, cost, schedule, preparation, leadership

1. Introduction

KSTAR, the Korea Superconducting Advanced Research, is a tokamak construction project, which began in December 1995 (Fig. 1) and was completed in July 2008 (Fig.2).

There are similarities and differences between KSTAR and ITER. But, one thing we should recognize is that they are both Nb3Sn based fully superconducting tokamak devices[1].

In the course of the KSTAR construction, we were excited from our achievements but also disappointed from our mistakes. At this presentation, we are going to highlight how much effort we made, how many trials and errors we experienced in order to overcome the difficulties we faced during the construction. In addition, we will share with you untold stories of the construction, hoping that our presentation will be of a good service to you. We begin with actual cases of eight critical sub-systems of KSTAR[2].

Fig.1 KSTAR project launch (29, Dec., 1995).

Fig.2 Ceremony for KSTAR first plasma (15, Jul., 2008)

2. Main Structure

Following the completion of the concept design in 1998, we started the engineering design in 1999 and finished in 2001. During this period, we managed to identify many engineering issues by manufacturing a real size 62 ° vacuum vessel sector. From 2001, the negotiation for the procurement contract was put in place with Hyundai Heavy Industries (HHI), and we signed the contract in May 2002. And for the next two years, we completed the fabrication of the cryostat, vacuum vessel and support structure[3,4].

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So, what really happened during this period? The first obstacle of the main structure construction was that it consumed too much time to conclude the actual procurement contract. What was the principal reason? An engineering design that was too idealistic and thus, lacked feasibility. Accordingly, we had to reassess the engineering design in full measure, taking into consideration actual conditions, such as manufacturer's capacity, material supply schedule, and the feasibility of required specifications. Then, we also decided to rearrange excessive design margins, which had been reflected in the existing construction, to reduce the cost. Still, the tolerances remained unreachable as they were initially set too high. All of the industries argued that it was impossible to maintain the welding distortion within a permitted limit due to an excessive load of welding. And the complexity of the structure made it difficult to conduct the non destructive test (NDT) as well as the formation of its shape. Furthermore, it was still too early to expect the industries to have a solid grasp of knowledge on the vacuum test on welded parts.

How did we resolve these problems and difficulties? Above everything else, we conducted a cost re-estimate. We firmly believe that the cost estimate should be based on the accurate estimate of the quantity of raw material. As long as you comprehend this method and process, you will not lose in the battle of price negotiation with suppliers. In the actual process, we examined the possibility to manufacture through a prototype and established the practical manufacturing method and process prior to the manufacture. And to minimize the risks, we made our best choice by adopting the most reliable methods. In other words, we ameliorated and applied proven technologies instead of introducing new, uncertain technologies. In some cases, we did mitigate the tolerance level. However, mitigating tolerance levels should not affect the performance of the device. What we are trying to point out is that taking the practical approach may enhance the reliability of the device. For example, we did try to improve the weld by attaching back plates to parts where the shielding gas could not be delivered. You might assume that using back plates may cause a corrosion problem. But it could be much more dangerous, particularly if you fail to successfully weld the parts with no back plates attached.

3. Thermal Shield

We carried out basic R&D and the concept design until 2002. In practice, more detailed design work was launched in 2002. The engineering design was provided by Air Liquide and the design for manufacturing was supplied by a local company called Wonshin. Then, we started to manufacture full-scale thermal shields in 2004 and completed in August 2006. We did this by assembling the last thermal shield of the vacuum vessel followed by the assembly of the cryostat thermal shields (CTS) in 2007. And the soundness of the CTS piping system was verified at the time of the vacuum commissioning for the entire cryostat[5].

In the beginning, we failed to make any substantial advances in spite of long R&D hours. Therefore, we were left with insufficient time for the real design and its manufacture. In its manufacture stage, the poor performance of Air Liquide, which was contracted to supply thermal and structural analyses on top of the concept design, resulted in an unstable management of schedule. Another difficulty we faced was to develop a procedure of assembly and assembling jig & fixtures for the vacuum vessel and vacuum vessel thermal shields (VVTS), because these two have different dimensions. Moreover, it was not easy to find out how surface condition of the plated thermal shields would affect the emissivity, and how the development of one of the core technologies, the silver plating technology, would turn out. But the most difficult part was figuring out how to efficiently lay out the cooling piping system, which is closely connected with the localization of the leak zone.

We reviewed a wide variety of manufacturing methods to avoid a vacuum leak and then conducted several preliminary tests in extreme conditions utilizing a prototype. The impact on the silver plated shield panel when it was exposed to the extreme environment was not as serious as we feared. As you all recognize, the vacuum leak issue is not a simple one. We did experience a vacuum leak at cryostat thermal shields (CTS), and it took us three months to pinpoint the exact spot as the manifold was not sufficiently subdivided. If the cryogenic valve was already installed, we believe it would have been much easier. This accounts for the importance of localization. And, we used bellows for joining some neighboring thermal shield sectors, considering heat shrinkage upon cooling. Based on our observations, it has high leakage potential. So, it is best not to use bellows. But if a leak is detected, this is the first spot to look into.

4. Superconducting Magnet

We invested the first two years in establishing the infrastructure for the concept design, its manufacture and the test. And for the next two years, the engineering design was completed along with the manufacture and test for the first cable-in-conduit conductor (CICC), as well as the facilities for coil manufacture. And then, we managed to manufacture 4 coils for the next three years by 2003. We will explain later why the progress got delayed. But the 7-year work period produced 4 magnets, yet we still had to make some decisions. What was left for us to do was to finish manufacturing 30 coils by 2006[6].

As mentioned earlier, the first problem we faced was that there were still too many issues to be resolved and decisions to be made. Even though we were confident with the R&D results of the superconducting magnet, it was still challenging to put the results into practice in the project execution. Additionally, the manufacturing process was not sufficiently evaluated or concretized at the specific engineering phase. Unfortunately, the fundamental problem was that we executed a construction project just like a R&D project. The reason why the magnet manufacture got delayed was due to the external interference and interventions concerning the performance of the CICC, which eventually caused a year-and-a-half amount of work stop. Without yielding to the difficulty, we put down the external criticism through a number of verification committees, which were composed of experts who inspected and verified the performance of the CICC. That way, we were able to resume the project. Nevertheless, major pending issues remained unsettled: the joint type, helium leak test method, fabrication procedure, and the delivery schedule of strand.

So, how did we solve these critical issues? The first step was to adopt a practical method to simplify the issues. For example, we made a decision on the joint type; there were some possibilities, such as the strand-to-strand (STS) joint, lap joint, and butt joint, with which we had been conducting R&D[7]. In the central solenoid (CS) coil, the butt joint was left out from the beginning due to small space. Therefore, the choices were limited to the STS and lap joints. The second step was to put our energies into the optimization of the actual manufacturing process. In case of KSTAR, the National Fusion Research Institute (NFRI) technical team carried out the coil manufacture at its early development stage. By doing so, they examined all the issues thoroughly and revised the process, then introduced the rigid quality control (QC) system and finally established a routine framework for the entire process. Not all processes reached optimization but the process as a whole was highly optimized. One of the successful cases was the helium leak test after jacketing. It was agreed that the sniff leak detector is the best method, but its reliability in effect was not as high as we expected. The actual limit of the most efficient sniffer detector is about 10^{-6} torr.ℓ/s. We adopted the bubble detection method of using a simple water bath in order to increase the reliability of its detection result. To our surprise, this method is quite simple and same as the process of finding a leak in a flat bicycle tube. In other words, you put a CICC spool into a big water bath, give it some pressure and wait to see when a bubble rises. This may seem like an elementary method, but as a matter of fact, it saves time and its detection limit is as reliable as 10^{-6} torr.ℓ/s.

As explained earlier, it was a challenging task to manufacture 30 coils in the given period of 3 years. So, we decided to build one more heat treatment furnace with a diameter of 6m and 5m in height, aiming to shorten the heat treatment process, which required an absolute time allocation. The new furnace had the capacity to treat 2 coils simultaneously as shown in Fig. 3.

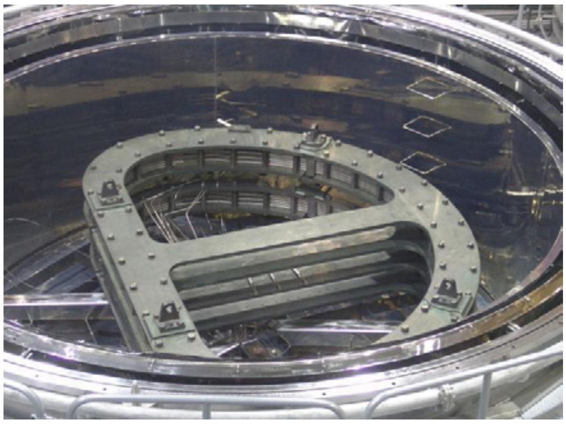


Fig.3 Heat treatment of two TF coils

Also, we outsourced some sub-tasks like taping and the vacuum pressurized impregnation (VPI) process, to small, local companies, so that they could train their manpower[8]. This saved NFRI a lot of time and helped the NFRI technical crew to focus mostly on inspection and supervision. In making such critical decisions, the most important factor is the self-confidence of the staff concerned with the performance of the project. Most of us almost gave up in the beginning because too many pending issues had to be resolved. However, we regained our confidence as we realized that the project could be put back on the right track through tight schedule management and quality control. What did we learn from all this? That sometimes, daring decisions can reverse a seemingly impossible situation in a favorable way.

5. Magnet Structure

We invested the first three years in concept design, the next two years in engineering design, and the following year-and-a-half in design evaluation. A company HHI manufactured the prototype, and we were able to establish the number of manufacturing processes during this period. Based on the actual manufacture contract with Doosan Heavy Industries (DHI), 4 structures were made in 2005. In March 2006, DHI delivered the last TF structure to the tokamak site. DHI also took the job of manufacturing and delivering the structures of CS and PF. This way, we managed to assemble the CS coil into the CS structure, successfully meeting the schedule as planned[4].

The first difficulty in manufacturing the magnet structure comes from the great amount of welding load for the magnet structures. It was difficult to control the fabrication tolerances, and it took relatively a long time to weld. Moreover, the most suitable conditions for VPI between coils and structures had not been examined yet, and it required a highly complicated procedure to manufacture one single structure. One of the challenges had to do with quality control of the welding of a cooling tube that was embedded within the structure. When a leak was detected after the VPI process was finished, the damage was almost irreparable. For the CS structure, it was most challenging to put its complex structure in order within a limited amount of space, as well as deciding the pre-compression level at a normal temperature assembly[9].

As for the complex welding process and its load, we controlled them by increasing the number of welders and developing an automatic welding device for certain kinds of work. We also made certain to leave a sufficient margin of fabrication, considering the final fabrication. The optimizing conditions for VPI were obtained through the mock-up test. Furthermore, we were able to tackle the complex manufacture process through staff training and a delay in schedule, which was based on the mutual agreement between NFRI supervisors and on-site workers. To prevent any leakage of the embedded tube, we used the thicker SUS tube than its original design, which improved the reliability of the welding by developing an automatic welding device. For the CS assembly, we placed 2 professionals in advance exclusively for its preparation for more than a year. Assembling the CS coil was the most difficult part for KSTAR. This may also be true for ITER. Because we perceived this problem beforehand, we thoroughly verified the preliminary assemblies a number of times based on 3D reproductions, as well as conducting several dry runs for an actual assembly by using dummy coil. Also during the process, we developed the special jigs & fixtures for pre-compression. These planned preparations ensured that the actual assembly ran like clockwork.

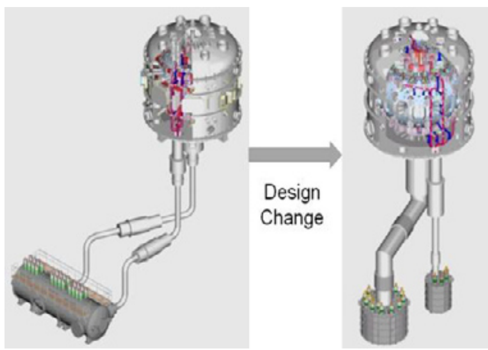
6. Magnet Interface

In February 2004, we concluded the final design and site plan for current lead system (CLS). However, the busline design and the routing of the He cooling tube were left undecided. As a result, we were pressured to do all the required tasks, such as finishing unsatisfactory design, manufacture and installation, within the next 4 years. We hurried to finish the engineering design of current lead box (CLB) and the busline by 2005 and completed their manufacture and installations in 2007. For the magnet interfaces, we conducted their integrated tests until February 2008, even after the completion of the cryo-plant)[10].

Several issues related to magnet interfaces were not taken into consideration at its initial stage of design. This was mainly because we invested most of our time and energy in the manufacture or test of the superconducting magnet. We were a bit late to recognize the importance of the magnet interfaces. The magnet is important, but it is just as critical to comprehend its interface issues, which would be the main cause of possible problems. When the design or manufacture of the superconducting magnets is delayed, so will the work of their interfaces.

The first principle of overcoming the difficulties is to simplify the numerous unsettled issues. For instance, you can set beforehand the boundary conditions for the location, shape and type for the interface devices. It goes without saying that you should target on the optimum conditions. Besides, we simultaneously carried out the design, manufacture and installation of the interfaces to catch up to schedule, and we decided to manufacture all the devices at home to meet the schedule and to reduce the cost. One effective result that I can tell you proudly is that it took only 9 months to manufacture 18 current leads. If they were contracted to a foreign supplier, it might have taken more than 2 years. You can see that it is highly critical to receive a fast response. In order to establish this fast response system between an employer and a contractor, you need to streamline the decision-making process and try to solve the problems happening at the work site through a weekly progress meeting. Moreover, we solved the technological puzzles by applying special technologies from different industries. For example, we applied a special type of adhesive material and a special coating measure, which are normally used in manufacturing a semiconductor board, in order to obtain lower joint resistance. In particular, recognizing that a joint or a busline could create problems during the prototype test, we carried out a number of preliminary tests at a temperature of liquid nitrogen and exhaustive quality controls at room temperature. Various destructive tests were conducted also.

The layout change of the current feeder system can be resumed as following. We separated the integrated CLB into 2 parts as shown in Fig. 4. This is because TF and PF account for two different stories when they come to the commissioning and electrical potentials. And we minimized the complexity of the busline by locating the CLB closer to the tokamak. In particular, by straightening the busline, the manufacture and installation of TF CLB became simple.



(a) Before (b) After

Fig.4 Layout change of current feeder system

7. KSTAR Assembly

We finished the basic design based on the current ITER Modular based scheme in 2002. We will explain later, but this method was troublesome to KSTAR. Therefore, we devised a new scheme and this enabled us to assemble the TF magnet piece by piece in rotation into a vacuum vessel. As the delivery schedule of components was indefinite, we agreed to fulfill the assembly contract in 3 stages. The 1^{st} stage was set to manufacture the main assembly jig & tool and to assemble the main supporting parts by 2004. The 2^{nd} stage was to complete the site welding of the vacuum vessel by 2005. And the last stage was to finish the assembly of the main tokamak by 2007[4].

First of all, we defined the assembly of the tokamak as a non-reversible process. However, there was room for certain parts, in which mistakes could be recovered, even during the assembly. Nonetheless, you must keep in mind that it is very difficult to repair or modify after the completion of the overall assembly. As different tasks take place at the work site concurrently, it is essential to allocate space efficiently. Especially, you need to take into full consideration the welding of distortions in the cryostat and vacuum vessel in advance. The actual tolerance of the superconducting magnet assembly was less than 1 mm. And because we had already fixed the assembly deadline, it was quite probable to cause an overall schedule slippage if one delivery failed. Also, the vacuum tightness of the last field joint remained as a huge obstacle.

First, you have to develop a perfect plan and preparation from the beginning to prevent mistakes in a multi-assembly process, which reflects actual on-site conditions. To do so, we took a full evaluation of the site welding using a 1/3 mockup of the real size. Then, we designed and manufactured the assembly jig taking into consideration an easy dismantlement in the future. The most challenging problem of the rotation assembly scheme for TF was figuring out how to assemble the last sector without a trace of leakage. Our solution was to carry out a vacuum leakage block by block, after installing vacuum chambers along the welded seam line.

Table 1 shows the comparison between a modular based scheme and a TF rotation assembly scheme. As you can see, a TF rotation assembly scheme has a number of advantages in tooling, working space, inspectability, accessibility, risk control and cost. The initial concept of the KSTAR assembly was the same as the current one of ITER. In other words, it was a modular based assembly scheme to make 1 module composed of 4 TF magnets. However, judging from important matters, like the layout of the assembly hall, delivery schedule, logistics and assembly tools, we realized that there could be some problems. This was an enormous concern. Because this meant that above all, the assembly required the assurance of space and a separate large-size sub-assembly tool. Furthermore, the technical difficulties of the 4 final field joints still existed. To overcome these difficulties, we adopted a new assembly concept: TF rotation. It did not need an additional large-size assembly tool or space. We planned to deal with all field joint problems in the last work phase. At first, people doubted the feasibility of inserting the magnet into limited space and the magnet rotating, because this seemed extremely demanding. In reality, however, this was very easy to assemble and did not take a lot of time. What is even more significant is that through this new attempt, our technical crew obtained the confidence to perform assembly work.

Table 1. Comparison of the assembly scheme

Item	Modular Based	TF Rotation
Tooling	Multiple, Huge	Single, Large
Space	More	On-site
Procedure	Complicated	Simple
Inspectability	Ordinary	Very Good
Accessibility	Ordinary	Very Good
Risk Control	Ordinary	Very Good
Working Time	Long	Short
Cost	High	Low
# of Site Joint	At least 4	2
TF Delivery	Tight	Reasonable

8. Magnet Power Supply

Like the preceding sub-systems, it took 2 years to complete its concept design. After having finished the manufacture of a testing prototype magnet power supply (MPS) in 2001, we completed its engineering design. More specifically, the PF MPS was composed of a ramping power supply (PS) and a flat PS. Then later by 2005, we manufactured 6 PF-MPS converters. But, we were left with one more TF-MPS and 7 PF-MPSs to be completed for the remaining 2 years[11,12]. We remodeled MPSs, which were previously used in a prototype coil test, into TF-MPS by reinforcing their quench protection (QP) circuit and control system, and then we inserted a blip resistor into all 7 PF-MPSs with a maximum current of 4kA.

The first difficulty in manufacturing a power supply system resulted from misunderstanding engineering priority. The power supply must be most active and stable in the tokamak device. Therefore, it has to be placed at the top of the priority list in the view of commissioning. Another concern was the ownership issue. As the manufacture of the power supply was contracted to another R&D institute, the ownership was weakly binding.

On top of that, there existed the difference between the two parties in understanding the scope of the work. Its manufacture was carried out under the management of a company POSTECH but its understanding was limited to the extent of a converter, contrary to NFRI's, which assumed that POSTECH would provide the entire power supply device. As a result, QP, transmitter(TR), busbar, control device and the surveillance device did not make any progress even after the R&D completion. Now you see why it is essential for a participating contractor to have a strong will to pursue its contract. We have concluded that one of the key elements to accomplishing the project is in knowing how to control the manufacturer. In addition to that, we neglected to determine how to arrange the external power supply line. Consequently, the entire integration of the power supply facilities fell into a predicament. But what was worse was that the budget for the power supply was downgraded.

At the end of 2005, everything was urgent and critical. The first emergency measure was to define the scheme of the MPS manufacture as soon as possible. We decisively altered the scheme of 2 MPS to 1 MPS+BRIS(Blip Resister Insertion System) scheme, and then we developed the commissioning scenarios for the new scheme. To catch up to the delayed schedule, we invested money for diagnostics and heating devices in manufacturing the power supply from 2006 to 2007. Additionally, we coordinated an all around multi-task team to perform several tasks simultaneously. And before anything else, we installed the complete power supply system in place and tested it at the site while using dummy coil. During the test, a great number of adjustments and arrangements were made. It may have been too optimistic to believe that the system would operate without a glitch on-site only because it performed perfectly at the factory test. Constant on-site adjustments and validation during the process served the operation simultaneously in the future. In fact, we hardly had any difficulty during the operation. The performance of the power supply system was very stable and exceeded our expectations.

9. Cryogenic Plant

After completing the engineering design, we requested its procurement contract in July 2002 and came to sign it at the end of December 2003. Air Liquide participated as a sub-contractor of a company SCEC for the cryo-plant construction. But the problem was that Air Liquide was a single vendor, and due to the dreary negotiation process, it took 18 months to conclude the contract. In the end, we had to sign the contract without covering the 2nd helium distribution system (HDS) part. From then on, we began the manufacture design and the actual manufacture got launched in September 2005. In March 2007, we started installing the cryogenic plant at the site and completed the commissioning in February 2008[13].

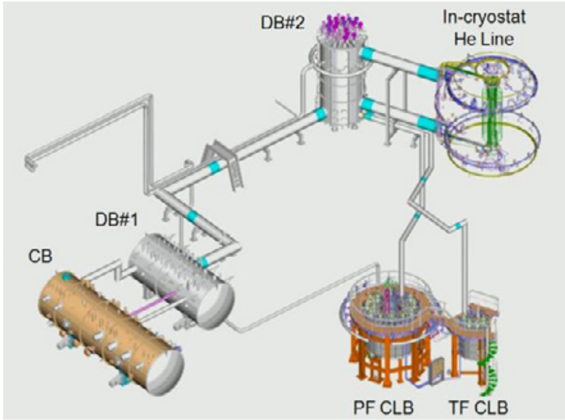


Fig.5 Configuration of helium distribution system

The complication of the cryogenic plant resulted from a lack of correct understanding about its relation to a superconducting magnet. As a matter of fact, we set to work without any expertise or an able staff. But the most challenging problem was that a procurement contract was signed too late. The fact that there was only a single vendor caused the price to rise, which reduced the contract scope, since the budget was fixed. And so, the 2nd HDS had to be left out.

To make up for lost time, we ran a special task team. But still, no progress on the 2nd HDS had been made until mid 2007 because of the budget crunch. I recall that this was the most critical period during the entire KSTAR construction: there was not enough time, budget, nor staff to manufacture the HDS. Fortunately, we managed to obtain the necessary budget for HDS in mid-2007 after passing the committee's investigation three times. But regardless of the given budget, it was already too late to meet the schedule if we followed the normal procedure. All the foreign companies were against the proposed schedule. Ultimately, we decided to do the job on our own in Korea under the leadership of the NFRI technical team, even though none of us had the appropriate expertise to do so. So, we hired outside experts to support us, and the KSTAR technical team led the work as a supervisor, manager and controller. After having considered the operation reliability and the entire cryo-system structure, we altered the layout of the 2nd HDS as shown in Fig. 5. This means that the 2nd HDS device was moved to the tokamak hall inside. As a result, the transfer line got relatively simple, and we could design and manufacture the distribution box with a clearance[14].

10. System Integration and Commissioning

The situation at the end of 2006, when the system integration could be resumed is as follows. The internal assembly of the cryostat was completed, but the engineering commissioning was not totally finished. Most of the remaining work was in figuring out how to finish the commissioning on the helium distribution system within the given schedule, as well as optimizing the PF-MPS for the first plasma[11-13]. Yet another obstacle was the fixed 2007 budget, in which there was no room for modification. In many aspects, it was quite difficult to achieve total integration because of these obstacles.

So how did we integrate the systems and generate the first plasma by a scheduled time? First of all, we reassessed every single sub-project and set the first priority as the generation of the first plasma. As I explained in the previous power supply section, we appropriated a large part of the budget to the PF-MPS work. However, the budget was still insufficient, and we had to change from full-spec to limited low current spec. From this decision, the ECH device emerged as an indispensible tool to generate the first plasma. However, the gyrotron tube was in a state of failure due to the collector water leakage at that time. To solve this problem, we urgently administered the gyrotron repair program[15]. Then, we prepared the installation of the 2nd HDS and the commissioning in a 2-shift system. Using the strategy of "Run and Hit," we began designing even before the contract agreement, in order to catch up to schedule. As for device control, we reorganized loosely managed tasks into mission-oriented ones and prioritized the essential tasks. In addition, we made a thorough preparation of a detailed engineering test scenario along with a daily-based plasma operation[16].

11. Summary

Lessons learned from the KSTAR construction can be summed up in the following 7 points. First, the success of the construction project depends on the harmony and balance among three important elements: schedule, cost and device performance. Second, the driving force of the entire project should be established before anything else. In case of KSTAR, we concluded the assembly scenario at the outset and then framed everything else into the scenario. Third, the significance of the vacuum, cooling and structure should be acknowledged. I believe that the details of these three points are the main factors in deciding the success or failure of the project. You should never overlook the importance of basics, because if you do, you will undoubtedly be putting the project at a great risk of failure. Fourth, it is essential for the industries to play an active role and strongly participate to achieve success in the project. In fact, the real capabilities and condition of the industries decide the concreteness of the engineering. Fifth, thorough preparation and constant self-criticism determine how well the device will perform. A mistake of one percent could set the stage for a perfect failure. If you want to secure a smooth commissioning, you have to concentrate even on this one percent. Sixth, the schedule and cost can be met only if there exists a strong leadership at the headquarters and a willingness to share the risks and hardships among the participants. Especially, making a definitive decision in time can save the project. Because the construction project is an acting matter, I cannot stress enough that it is highly important for a leader to make a correct judgment of the circumstances. Seventh, the participants should be open and ready to do whatever is necessary for the project. The project cannot be a success as long as any participant stays passive. All the participants can reap the fruit of success from the project if they all internalize and understand the critical challenges to complete each step of the construction and at each step, put in the necessary efforts.

Acknowledgment

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References

[1] G. S. Lee, et. al., Nuclear Fusion **41**, p1515, 2001.

[2] J. S. Bak, et. al., Cryogenics **47**, p356, 2007.

[3] J. S. Bak, et. al., IEEE Transactions on Plasma Science **32**, p757, 2004.

[4] H. L. Yang, et. al., Nuclear Engineering and Technology, **40**, p439, 2008.

[5] G. H. Kim, et. al., Fusion Engineering and Design, **84**, p1043, 2009.

[6] J. S. Bak, et. al., Fusion Engineering and Design, 81, p2315, 2006.

[7] S. Lee, et. al., Physica C **468**, p417, 2008.

[8] H. T. Kim, et. al., JKPS **49**, p263, 2006.

[9] J. W. Sa, et. al., "Assembly results of the KSTAR CS Coil System", 5th IAEA TM on SSO, Daejeon, Korea, 2007.

[10] Y. M. Park, et. al., IEEE Transactions on Applied Superconductivity, 19, p1587, 2009.

[11] J. H. Choi, et. al., Nuclear Engineering and Technology, **40**, p459, 2008.

[12] Y. Chu, et. al., IEEE Transactions on Applied Superconductivity, 19, p1565, 2009.

[13] Y. S. Kim, et. al., IEEE Transactions on Applied Superconductivity, **19**, 1577, 2009.

[14] Y. J. Lee, et. al., IEEE Transactions on Applied Superconductivity, **19**, 1582, 2009.

[15] Y. S. Bae, et. al., Fusion Science and Technology, 55, p56, 2009.

[16] Y. K. Oh, et. al., Fusion Engineering and Design, 84, p344, 2009.