Value Engineering in System of Cryoline and Cryo-distribution for ITER: In-kind Contribution from India

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Abstract. System of Cryoline and Cryo-distribution for ITER has matured to a stage of preliminary design with the advent of industrial associates. Starting from the cold power source, the system of Cryoline and Cryo-distribution transfers the controlled cold power through a large network to the superconducting magnets and cryopumps. The functional responsibility also includes very high reliability and availability with respect to the operation of the ITER machine. Following the completion of conceptual design, it was necessary to perform a detailed engineering study of the complete network of distribution system in totality, before entering in to the industrial phase. This is to ensure the functional responsibility of the system. Value engineering in the area of distribution boxes including interfacing Cryolines has been performed in order to access the integrated reliable performance with respect to the overall cryogenic system, reducing the risk transferred to the industrial partners. These include technical risk assessment, analysis, mitigation plan and implementation with the industrial partners. The paper describes the methodology of technical risk management, value engineering performed to ensure fulfilment of licensing and regulatory obligations, functional reliability, testing and manufacturability by standard industrial processes, so that highly reliable integrated distribution system is delivered for the project.

1. Introduction
ITER is a unique project on fusion, being built at Cadarache, France and the first of its kind fusion reactor, to be licensed for operation as a nuclear establishment. The specific systems, specially integrated inside the Tokamak building requires to follow certain specific norms. Some sub-systems of the overall ITER cryogenic system, falls under this category. The ITER cryogenic system consists of three main subsystems; the Cryoplants, the Cryo-distribution (CD), as well as the system of Cryolines (CL) and Warm line (WL) systems [1]. The Cryoplant provide the required cooling power for the clients, namely, the Superconducting Magnet (SCM) system, Cryo-pumps (CP) and thermal shield for the main cryostat. The CD and CL systems are part of the in-kind supply from India. The CD comprises of nine cryogenics distribution boxes having different functions, to be specific, one Cryoplant Termination Cold Box (CTCB) and five Auxiliary Cold Boxes (ACBs), one Cold Compressor Box (CCB) and two Thermal shield Cold Valve Boxes (TCVBs) as per the accepted conceptual design [2]. The CL system interconnects the subsystems through a well-defined network to fulfil the global functionality of cooling the cryogenic components at three main nominal temperature...
levels, 4 K, 50 K and 80 K. While the CD system controls and regulates as per the different operational scenario of the ITER clients, the CL system establishes the two way communication of the required flow of cryogen as per the ITER cryogenic process with the structured network of multi (two to seven) and single process pipe CLs. Due this complex execution of the project as an integrated system, it was understood that each system have to be accepted as standalone, before interfacing with each other. Therefore, associated technical risks were obvious and called for an efficient mitigation mechanism within the project limitations.

2. Work Description
Having understood the (i) complexity in the stringent specification and combinations of load conditions, (ii) limitations on site requirements, layouts, and interface requirements, (iii) choice of applicable codes and standards, (iv) fulfilment of French decree 99-1046, French order 21 December 1999, (v) safety and quality requirements, the first major identified risk was availability of limited resources of industrial partners for execution of the project. The first of a kind nature led to an understanding that the learning curve will be having rather flat slope, leading to inefficiency in the execution. Therefore, technological and technical risk assessments [3] were carried out with weighting factors for measuring the seriousness and impacts.

3. Project Risk and Identification
The risk drivers and ranking were made based on risk categories, namely, technology, interfaces, safety, site characteristics, quality requirement, regulatory requirement, level of complexity due to nuclear environment, contractor’s capabilities, number of key participants and schedule.

The technical risk register, consisting of risk drivers, has been considered as a live document. Due assessment of the first set of identified risks revealed that both qualitative and quantitative mitigation mechanisms are required with time bound and time evaluated processes. The identified risks had both direct and indirect impacts on the technical performance of the system in consideration, i.e. CD and CL. The transfer of knowledge, know-how respecting the intellectual proprietary rights were given due importance. The risk management process followed the specific path as (i) Identification, (ii) Assessment, (iii) Impact Determination, (iv) Monitoring (v) Reporting and (vi) Risk Closure.

Specific considerations of risk drivers in the present work has been considered as (i) First of a kind Design (ii) Management of establishing too many interfaces, (iii) Interface Load, (iv) Compatibility of material, (v) Compliance with French nuclear safety, (vi) Space constraints and layout, (vii) Quality and (viii) Regulatory requirement.

Table 1. Likelihood and Impact Matrix.

| Likelihood of Occurrence | Negligible (1) | Marginal (2) | Significant (3) | Critical (4) | Crisis (5) |
|--------------------------|----------------|--------------|-----------------|--------------|------------|
| Very Likely (5)          | Low (5)        | Medium (20)  | High (45)       | Very High (80) | Very High (125) |
| Likely (4)               | Low (4)        | Medium (16)  | High (36)       | High (64)    | Very High (100) |
| Unlikely (3)             | Low (3)        | Medium (12)  | Medium (27)     | High (48)    | High (75)  |
| Very Unlikely (2)        | Low (2)        | Low (8)      | Medium (18)     | Medium (32)  | High (50)   |
| Not Credible (1)         | Low (1)        | Low (4)      | Low (9)         | Medium (16)  | Medium (25) |

4. Risk, Analysis and Mitigation Basis
Each of the identified risks were then analysed based on the discrete weighing factors in terms of occurrence (O) and impact (I) with a correlation of rank (R). The ‘likelihood of Occurrence’ – ‘Impact’ matrix was formulated based on the correlation as \( R = I^2 \times O \) as shown in table 1 with four rank zones as low, medium, high and very high. The basis for selection of rank zones is as follows, low – no technological and technical risk, medium – no technological but low technical risk, high – low technological but high technical risk, very high- high technological and technical risk. The major
reduction in the occurrence and impact were observed due to the consideration for proto-typing both in CL and CD. A consequential impact on reduction of risk ranking due to implementation of the proto-typing and further launching in the value engineering were noticed in the risk categories, mainly, safety, site, quality, regulatory, radiation as shown in figure 1.

Figure 1. Risk ranking (original and mitigated) profile with respect to risk categories for CD and CL.

5. Value Engineering
Following the risk assessment, mitigation actions, the prototypes were developed for both CL and CD under a highly collaborative association with the industrial partners. The development of prototypes further facilitated in executing the value engineering of the CL and CD system.

5.1 Cryolines
ITER CLs consist of 37 types of vacuum jacketed CLs spread over the Tokamak building, plant bridge and cryoplant building. The routing of the ITER CLs is very complex with large number of bends at odd angles, branches and tight positional tolerances due to limited space availability. The extensive technical specifications along with stringent quality, safety and regulatory requirements call for highest standards in terms of design, manufacturing and performance for these CLs.

5.1.1 Planning and Synchronization
The planning and synchronization for development of Prototype Cryoline (PTCL) with the ITER CLs has been coordinated in a way to minimize the technical uncertainties. The successful completion and acceptance of PTCL design has been considered as the first milestone required to start the preliminary design of the ITER CLs. The successful completion of manufacturing and factory acceptance test (FAT) of PTCL provides essential technical feedback and knowhow to start final design of the ITER CLs. The lessons learnt on PTCL will be then utilized to develop the manufacturing design of the ITER CLs with reduced risks. The successful completion of cold testing of PTCL has been considered as an important input to start manufacturing of the ITER CLs.

Following the due market survey, the technology risk touched the high risk zone due to the availability of ‘limited resources of industrial partners’ and their understanding on the technical specifications. This identified risk was found to have both direct and indirect cascading impact on the technical performance of the system of CLs for ITER. A four-step process was then implemented starting from global expression of interest with pre-qualification, PTCL design followed by fabrication and test. The technical specifications for PTCL were chosen carefully to exemplify one of the most stringent specifications of the ITER CLs as shown in table 2. The conscious decision to use EN and PED harmonized standards for design, fabrication and materials for the ITER CLs was taken to satisfy the requirement of ‘CE marking’ as the final use of the components will be in France.
Two PTCLs were designed by two industrial partners through collaborative approach. The two different designs were reviewed by experts and accepted based on the technical inputs and design outcome as shown in figure 3. The major outcome of two PTCL designs are summarised in table 3. The technical uncertainty of the overall CL system was mitigated by selecting particular segments in the PTCL such as Tee, C-sections with different angles, straight section and a specific out of plane Z sections. This exercise tremendously improved the confidence level of the industrial partners. The overall execution of the ITER CLs was then taken up with fabrication and testing of the PTCL. Correspondingly, a dedicated test facility was created to suit and support the cold testing of the PTCL.

The PTCL is under manufacturing by one of the industrial partner as shown in figure 3 and will be cold tested at tailor made test set-up at ITER-India laboratory [4] as shown in figure 4 to assess and validate their thermal performance at cryogenic temperature as well as to ascertain its mechanical integrity. The manufacturing of the second PTCL is at the verge of starting. The various options for heat load measurement and cold testing of PTCL has been already investigated and optimized [5].

| Specifications | ITER CLs | PTCL |
|----------------|----------|------|
| OVJ Size       | DN 100 to DN 1000 | DN 600 |
| No. of process pipes | 1 to 7 | 6 |
| Length         | ~ 5000 m | 27 m |
| Segments       | Straight, Tee, Elbow, Z | Straight, Tee, Elbow, Z |
| Quality Classes (QC) | QC 1, QC 2 | QC 1 |
| Seismic Classes (SC) | SC1 (SF), SC1 (S), SC2, NSC | SC1 (S) |
| Safety Classes | SIC-II*, SR, Non-SIC | Non-SIC |
| Fluids         | Helium, Nitrogen | Helium |
| Temperature levels | 4.5 K, 50 K, 80 K, 300 K | 4.5 K, 80 K, 300 K |
| Pressure of process fluid | Maximum 21 bar | 21 bar (design) |

[NSC: Non Seismic Class, Non-SIC: Not Safety Important Class, SC1(SF): damage limit ‘normal’ as per code for Seismic Level-2, SC1(S) and SC(2): damage limit ‘faulted’ as per code for Seismic Level-2, SIC-II: Safety Important Class component which is part of secondary confinement boundary for nuclear establishment – stringent quality control and inspection by nuclear authority, QC1: 100% volumetric inspection, QC2: typically 20% volumetric inspection]

| Specification         | Criteria                  | Design-1 | Design-2 |
|-----------------------|---------------------------|----------|----------|
| OVJ size              | ≤ DN 600                  | DN 600   | DN 600   |
| No. of internal fixed supports | N.A.                      | 7        | 8        |
| No. of internal sliding supports | N.A.                      | 9        | 9        |
| No. of external supports | N.A.                      | 8        | 12       |
| Average weight (kg/m) | Shall be minimized         | 376      | 254      |
| No. of segments       | Shall be minimized         | 4        | 5        |
| Average heat load at 4.5 K (W/m) | ≤ 1.2                     | 0.88     | 0.98     |
| Average heat load at 80 K (W/m) | ≤ .45                     | 4.33     | 3.73     |

5.1.2 External supports for Cryolines inside Tokamak building
The ITER CLs will be installed at various locations at the ITER site fixed to various types of external supports. These external supports are connected to Embedded Plates (EPs) of various load bearing capacities all along the CL routings. The Configuration Model (CM) developed for the layout at the conceptual design stage considered sharing of many CLs in a single support using many EPs. The
basic functions of EPs are to transfer the CL loads arising during the different operational scenarios due to the several load combinations via the external supports to the Tokamak building.

Figure 2. Two designs of PTCL – cross sections and configuration.

Figure 3. PTCL manufacturing progress.

ITER CLs are to be installed on a different time scale, therefore, time synchronization between different CLs for installation on a common support led to severe complexities due to availability of limited adjacent space. In addition to this, one more complexity in the execution is participation of more than one industrial partner for execution of the ITER CLs. In order to simplify the installation complexities, a detailed study led to the value engineering in which it was possible to separate out the common support, meaning thereby an individual group of CLs are assigned with individual supports with respective EPs.

The basis for the separation of supports and assignment of corresponding EPs were; (i) Span length requirement between two support (ii) Forces and moments arising from CLs of different size due to various load combinations e.g. thermo-mechanical + seismic (iii) Endorsement to the location of anchoring points (iv) Attention to the singularities in layout e.g. Elbow, Tee. Figure 5 (a) shows schematic example of common support while figure 5 (b) shows schematic example of supports after separation of EPs. Figure 5 (c) shows separation of EPs inside Tokamak building.
5.2 Cryo-distribution
The CD system of ITER is specifically configured for a fusion machine, meaning thereby managing the steady state heat load, dynamic heat load arising from the magnets system as well as nuclear heating and supporting the operational scenarios [2].

5.2.1 System Optimization
In order to support the operational scenarios of the ITER machine as regards to operational temperatures of the SC magnets and Cryopumps (CPs), the five ACBs were configured with ‘LHe baths’ at different temperatures. In order to achieve the desired configurations, cold compressors were implemented individually at the ACB PF (poloidal field coils) and ACB CP.

The ‘LHe bath’ of rest of the ACBs, namely, ACB ST, ACP TF and ACB CS were then connected to one common cold compressor, which required a separate cold box, designated as CCB. The common cold compressor configuration, as shown in figure 6(a), requires cold compressor of capacity ~2.1 kg/s. This requirement can be fulfilled with two options, either upscaling or use of two small cold compressors with parallel configuration; however, in both the options the question on reliability remains with the same gravity. The system optimization study carried out showed a clear advantage of having individual cold compressor in each ACB, as shown in figure 6(b). A common CCB is then not required leading to simplification in system configuration. Individual cold compressor in each ACB also provides flexibility to operate LHe bath in each ACB at different temperature level. Maximum mass flow rate requirement of the cold compressors is reduced to 0.6 kg/s, 0.8 kg/s and 1.3 kg/s for ACB TF, CS and ST respectively, which is in the present industrial range of products, therefore, reduced significantly the uncertainty involved in upscaling.

5.2.2 Test ACB
In order to develop confidence on the overall technical know-how and the requirement arose from qualification test of the cold circulating pumps (CCP), a Test ACB (TACB) has been developed taking
in to account the technical requirements of the major components of a typical ACB such as valves, heat exchangers, filters, instrumentation etc. TACB has been designed with industrial collaboration and the manufacturing of the same is near completion. The quality plan of TACB has been developed keeping in mind all the requirements of CD system ACBs. Implementation of this during the TACB development process has developed data and know-hows which have been considered as blessing while developing the preliminary design of the ACBs. Figure 7 shows the TACB developed.

(a). TACB 3D model.                        (b). TACB Manufacturing Progress.

Figure 7. TACB design and manufacturing

5.2.3 Cold Circulating Pump
The CCP for supercritical helium are the specific components of the CD system on which operational availability of the whole ITER machine depends. This is first of a kind technical specification in terms of mass flow, pressure head and variation in input conditions, that is, temperature and pressure [6]. In all modes of operation inclusive of 110 % of mass flow, more than 70 % efficiency was demanded. Based on the preliminary market survey, the industrial partner’s concern to respect the specifications was obvious. Therefore, a systematic approach was followed in a step wise manner.

(a) Before Optimization                                    (b) After Optimization

Figure 8. Temperature on CCP top flange leading to optimization of thermal intercept

Having known the shortcomings in the technical regime of the specifications, choice of technology, an approach was taken to develop two CCPs with the two different (active magnetic and ball) bearing technologies. During this development through the highly collaborative work with industrial partners, the design iteration led to the optimization of the on-cryostat mounting flange where cold temperature was observed as shown in Figure 8 (a). This is a non-trivial issue for the case of CCP, although simple increase in the separation between the on-cryostat mounting flange and the thermal intercept can be considered as one of the solutions among others, e.g. using heater or reducing cross-sectional area. However, the solutions have to be in synchronization with the specification as it may impact on the
efficiency, which will then lead to non-conformance of the specification. Therefore, the technical solution adopted as shown in Figure 8 (b) provides one representative example leading to the value engineering by optimization on the position of thermal intercept keeping the required efficiency as well as without inclusion of any additional components and/or controls. Analysis shows that it has been possible to increase the temperature from 289 K to 298 K satisfying the requirement. The uncertainties identified during the preliminary assessment were also addressed with proper technical actions such as thermo-mechanical analysis, rotor dynamics, small prototyping and tests at 80 K [7].

6. Conclusion
The detailed study has been carried out to identify and assessing the technology as well as technical risk for CD and CL system. The methodology developed to manage and mitigate the technical risk was implemented both at project and industrial level. The development of the two prototype cryolines by two industrial partners satisfying the ITER project requirements has reduced the technology risks to the manageable medium level and also leading to value engineering in terms of design optimization. Proper planning and synchronization has led to the minimization of risk during the construction of cryoline at ITER site using the EPs. Development of two CCP and the value engineering performed led to an optimized design mitigating the technological risks. Further, development of TACB has mitigated the technical risk of the CD system. The harmonization of risk assessment and value engineering has developed confidence both at project and industrial level to deliver an integrated and reliable CD as well as CL system for ITER.

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8. Disclaimer
The views and the opinion expressed herein do not necessarily express those of the ITER organization and the ITER partners.

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