

Status of ITER Cryodistribution and Cryoline project

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Abstract. The system of ITER Cryodistribution (CD) and Cryolines (CLs) is an integral interface between the Cryoplant systems and the superconducting (SC) magnets as well as Cryopumps (CPs). The project has progressed from the conceptual stage to the industrial stage. The subsystems are at various stages of design as defined by the project, namely, preliminary design, final design and formal reviews. Significant progresses have been made in the prototypes studies and design validations, such as the CL and cold circulators. While one of the prototype CL is already tested, the other one is in manufacturing phase. Performance test of two cold circulators have been completed. Design requirements are unique due the complexity arising from load specifications, layout constraints, regulatory compliance, operating conditions as well as several hundred interfaces. The present status of the project in terms of technical achievements, implications of the changes and the technical management as well as the risk assessment and its mitigation including path forward towards realization is described.

1. Introduction

ITER is the next frontier research tool for harnessing fusion as a viable source of energy, when built and operates, presently under construction at Cadarache, France. It is also the first of its kind fusion reactor, to be licensed for operation as a nuclear establishment. ITER will confine D-T plasma in a Tokamak configuration having $Q=10$; therefore, requirement of high magnetic field and efficient vacuum environments are indispensable. ITER will use SC magnets, namely 18 Toroidal Field (TF), 6 Poloidal Field (PF), 6 modules of Central Solenoid (CS), 9 pairs of Correction Coils (CC) and large CPs to fulfill the technical necessities for confinement of the hot plasma. A heavy cold structure (STR) is also foreseen to support the forces and moments arising due to the large electromagnetic forces as well as the substantial dead weight. The ITER TF magnets will operate at very high current, approximately at 68 kA [1]. The need of a large cryogenic system is self-explanatory then due to the operation of large SC magnets and CPs as all the cold masses are required to be maintained at 4 K temperature level to get the efficient performance.

The basic configuration foreseen for the cryogenic system for ITER is represented in Figure 1. Major sub-systems are i) the Cryoplant consisting of 3 identical liquid helium (LHe) plants, 2 identical 80 K loops and liquid nitrogen (LN₂) plants including LHe, gaseous helium (GHe), and LN₂ storages; ii) the CD system; and iii) the CL system intra and interconnecting the Cryoplant, CD and the clients [2]. The integration of all the systems together is the basic and foremost challenge, as procurements of the sub-systems are made by different agencies. In order to maintain the high level of efficiency while

sustaining quality and safety, a close co-ordination has been foreseen and implemented to manage the risks. The Indian Domestic Agency (INDA) is responsible for supplying the system of CLs, warm lines and the CD system along with requisite controls. The system engineering approach was employed to manage the internal interface risks. The project and technical risk analysis at an early stage of the project ensured smooth take-off.

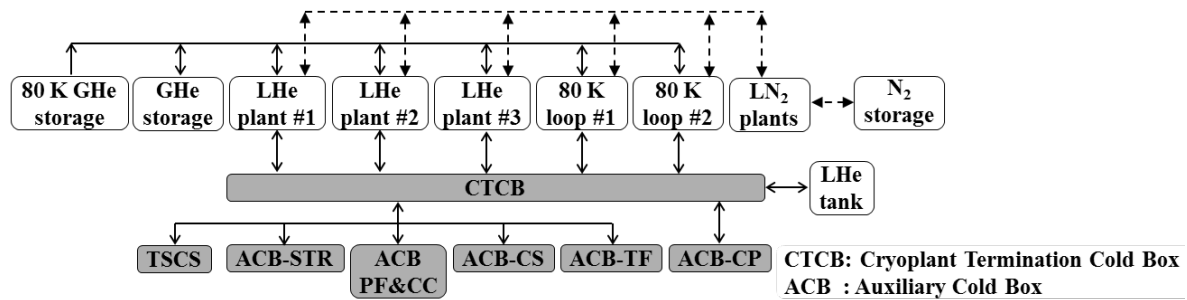


Figure 1. Basic configuration of ITER cryogenic system

The procurement of the system of CLs started in the year 2010, followed by design of prototype CL and its acceptance, a basis then to follow and select the qualified bidders. The activity of the design of prototype CL benefited on over all understanding of not only the project team, but the industrial partners as well, mitigating the risks further. A brief summary of the progress made towards procurement of different systems with the industrial partners are represented in Table 1.

This paper describes the specificities on the technical, contract and project management for the benefit of the cryogenic community, where a highly coordinated activities and management are required as well as technical progress made so far for the ITER CD and CL project.

Table 1. Involved Industrial partners for ITER CD and CL system.

System	The partner	Date of contract signature
CL (Group-Y: up to three process pipes)	M/s INOX India Limited and M/s A S Scientific	Design of Prototype CLs: February 2011 and Group – Y: April 2014
CL (Group-X: 4 to 7 process pipes)	M/s Air Liquide Advanced Technology (ALAT)	Design of Prototype CLs: February 2011 and Group – X: July 2015
CD system	M/s Linde Kryotechnik AG	September 2015
TF - Cold Circulator	M/s Barber Nichols Inc.	January 2014
TF - Cold Circulator	M/s IHI Corp.	January 2014
Test-ACB – for Performance test of cold circulators	M/s Taiyo Nippon Sanso Corporation	August 2013
Warm line	M/s INOX India Limited	July 2015

2. Scope and Road map

The ITER project has recommended set pathways for the overall project which is represented schematically in Figure 2.

The set pathways were then mapped in to the project planning of the system of CL, warm line and CD project. The broad functional scope for all supplies under the INDIA scope are (I) To distribute cold power to the clients (namely, magnets, Tokamak thermal shield and CPs) through supply of cryogens at proper temperature, pressure and flow (II) To perform the safety functions in case of failure. The broad scope for all the three projects are, (i) Preliminary Engineering Design (ii) Final Engineering Design (iii) Manufacturing (iv) Factory Acceptance Test (v) Site installation (vi) Conducting site acceptance test and (vii) Integrated cold test, each scope to be followed by a project review. System requirements, specific to the CD and CL system, such as layout, codes and standards, quality, safety, regulatory, seismic and load combinations were folded in as technical requirements.

Visible differences were seen among the scope of supplies, as one system is highly process oriented, whereas the others were more on maintaining the mechanical integrity. The physical deliverables are summarized in Table 2.

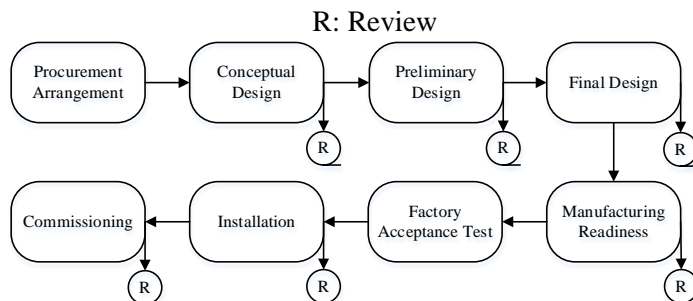


Figure 2. Roadmap for project execution of ITER cryogenic system

The road map for execution of the project from procurement to final execution for the system of CLs, warm lines and CD were laid differently at the beginning of the project. It was understood that a proper supply chain management needs to be established for the system of CLs and warm lines, whereas for the CD system, a rather specific and customized ‘cold box’ industrial approach is required. Based on this hypothesis, the project execution began.

Table 2. Summary of physical deliverables

Sl. No.	System	Supplies	Details
1.	CD System	(i) ACB	(i) Five cold boxes ACB-TF, ACB-PF&CC, ACB-CS, ACB-STR, ACB-CP
		(ii) CTCB	(ii) One cold box
		(iii) TSCS	(iii) One cold box
2.	System of CLs	(i-iv) Helium at 4 K level – ~2 km	(i) CLs between CTCB and Cryoplant (ii) CLs between CTCB and ACBs/TSCS
		(i-v) Helium at 80 K level – ~2.5 km	(iii) CLs between ACBs and magnet clients (iv) CLs between ACB-CP and CP clients
		(vi) Nitrogen at 80 K level – ~0.6 km	(v) Quench and relief line (vi) LN ₂ lines
3.	Warm line	~6 km	All warm lines

3. Project Requirements

Technical requirements, as defined for the project are mainly client based. Table 3 describes the functional requirements for the magnets and CPs, which are expected from the CD system.

Similarly, the flow from the cold circulators in the CD are to be distributed to the TF, PF, CS, CC magnets as well as STR and to the CPs through the CLs. Acceptable heat load for the system of cryolines is 2.6 kW at 4.5 K, 6.2 kW at 80 K and for CD, 1.3 kW at 4.5 K and 3.9 kW at 80 K. Out of the two options available to follow the codes and standards ASME and EN, a conscious decision was taken to follow the EN / ISO standards for the projects under the scope of INDA, due to ease for complying with CE marking, conformity and harmonization with the global project.

Apart from the technical requirements, project imposed system classifications are (i) Safety Importance Classification (SIC): Non Safety important, Safety relevant, SIC-2 (ii) Quality Classification (QC): QC 1, QC 2, QC 3 and QC 4 (iii) Seismic Classification (SC): Non-Seismic, SC2, SC1 (SF) (iv) Vacuum Quality Classification (VQC): VQC 4A/B [3]. Each of these classifications have specific meaning and to fulfill certain functions in terms of design conformity. Three events of seismic level (SL) spectrum are to be considered for the designs, which are Cadarache site specific,

SL1, SL2 and Maximum Historically Probable Earthquakes (SMHV). Site specific requirements to be adhered to are (i) French Decree 99-1046 dated December 13, 1999, amendments 2003-1249 and 2003-1264 (ii) French order of December 21, 1999 (iii) INB order of February 07, 2012 [3]. These regulatory requirements ensure proper classification, identification of category and evaluation of conformity of the pressure equipment in a nuclear establishment. The major codes and standards followed for the CD and CL project are described in Table 4.

The experience of implementation of the codes and standards were followed in the prototypes as well for global understanding.

Table 3. Functional process parameters for magnets and CPs

Operating Condition	Parameter	CS-cold circulator	TF-cold circulator	STR-cold circulator	PF&CC-cold circulator	CP-cold circulator
Common inlet conditions in nominal, maximum flow and maximum head operations	P_{in} (MPa)	0.51	0.46	0.56	0.51	0.34
	T_{in} (K)	4.3	4.3	4.3	4.3	4.3
Nominal operation	Mass flow (kg/s)	2.07	2.21	2.62	1.93	1.36
	ΔP (MPa)	0.1	0.15	0.05	0.1	0.07
Maximum flow rate operation	ΔP (MPa)	0.1	0.15	0.05	0.1	0.07
Maximum pressure head operation	Mass flow (kg/s)	2.07	2.21	2.62	1.93	1.36

Table 4. Major codes and standards

Sl. No.	Purpose	Code
1.	Construction	EN 13480
2.	Pipes	ISO 1127
3.	Welding	ISO 5817, ISO 14731, ISO 14343, ISO 14344
4.	Safety Devices	EN 764, ISO 4126, EN 13648
5.	Cryogenic valves	EN 1626, EN 60534-2-1, AD 2000, PED 97/23/EC
6.	Non Destructive Testing	ISO 17636, EN 12517, EN 473, ISO 17636

4. Risk analysis, Mitigation and Interface management

The technical and project risks [3] at the early stage of the project made efficient execution and implementing the strategy into practice. The major risk drivers were found to be (i) First of its 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. A focused risk management process were placed in position as (i) Identification, (ii) Assessment, (iii) Impact Determination, (iv) Monitoring (v) Reporting and (vi) Risk Closure. Identified risk categories were mainly for technology, interface, safety, site, quality, regulatory and radiation. The risk categories, which were in the 'Very high' and 'High' regime, were brought to medium and low level with the mitigation actions, mainly due to early prototyping for LS and the cold circulators as well as value engineering.

Specific example for the cold circulator risk analysis is described. The review of presently operational machines reveals that maximum mass flow rate of 1.2 kg/s with pressure head of 0.4 bar

[4]; designed, manufactured and supplied by the industries. The demand for SC magnets and CPs for ITER have been described in Table 3. Such demand asks for technological improvements in terms of upgrade of the existing cold circulators or development of new design. Predicting and prevention of potential failure of such machines at an early stage of design would reduce the risk and cost in future. The 'Failure Mode, Effect and Criticality Analysis (FMECA)' has been an effective tool to address the issue of reliability for the cold circulators to ensure the performance in realistic operating condition, at the design stage of the project. Systematic approach for FMECA has been adopted through Xfmea® [5] software. The impacts of functional failures of the cold circulators have been judged at wider level with an aim to have minimum down time for ITER. Severity and occurrence scale thus adopted [6] in five discrete weight factors as described in Table 5.

Table 5. Severity and occurrence scale for ITER the CD and CL system

Severity	Weight factor	Criteria (Plasma operation non-availability time t)
less severe <4 hours	1	$t < 4$ hour
Moderate severe <1 day	2	4 hour $< t < 1$ day
Severe <1 week	3	1 day $< t < 1$ week
Very severe <1 months	4	1 week $< t < 1$ month
Critically severe > 1 month	5	$t > 1$ month
Occurrence	Weight factor	Criteria (Occurrence O)
Very Low	1	$O < \text{once}/100$ years
Low	2	$O < \text{once}/10$ years
Moderate	3	$O < \text{once}/\text{year}$
High	4	$O < \text{four times}/\text{year}$
Very high	5	$O > \text{five times}/\text{year}$

Based on the analysis approach, the risk assessment in the Xfmea® with defined Severity (S) and Occurrence (O) rating in the scale as mentioned in Table 5 has been performed. The results obtained from the FMECA analysis is represented in Figure 3(a). The Criticality (C) is obtained as the product of S and O. The co-ordinates (S, O) of all effects and causes are placed on the criticality chart of Figure 3(a). The high (Zone-1), medium (Zone-2) and low (Zone-3) risks, depending on the criticality threshold have been defined to categorize the risk level. Criticality higher than 11 has been identified as high risk for the reliable operation of the cold circulators. Similarly criticality between 11 and 5 has been defined as medium risk whereas, criticality below five has been considered as low risk. Total 10 major risks have been initially identified based on the analysis carried out. Risk identified at the medium level is 9 and at lower level 5, thus identifying total 24 risk in the present study as shown in Figure 3(a).

In order to reduce the risk level associated with the failure mode identified in FMECA, risk mitigation actions have been initiated in two steps (i) step-1: component level test (ii) step-2: prototype test of cold circulators in operating conditions, considering the overall cost factors. These actions are distinguished by the way they reduce either the occurrence or severity of failure mode, thus affecting the criticality. Controls have been implemented with initiation of actions to reduce the criticality of high risks. The major actions focused on the step-1, to mitigate the high risks are (a) component test which are prone to failure for reliable operation (b) adoption of proven technologies (c) consideration of higher margins in design. The criticality is again reviewed in the same scale of criticality threshold ($C=5$ and 11). The criticality thus obtained after the actions of step-1 is shown in Figure 3(b). Out of the 10 major risks before applying mitigation actions (step-1), 4 high risks still remained and remaining 6 high risks moved in the medium and low level. In order to further minimize the residual risk, second level of mitigation action was applied in the step-2. No high risks remained after implementing the step-2 risk mitigation in to account. Reduction of severity and/or occurrence allowed the reduction of criticality of the failure modes and removed them from high risk zone with

mitigation actions outlined above. Figure 3(c) shows that no risk has been identified above the high criticality threshold ($C=11$), however, risk at medium level increased from initial value of 9 to final value 15, following the risk mitigation actions.

The analysis above mitigated the complete project risks, investment cost and functional interface management of the ITER CD system.

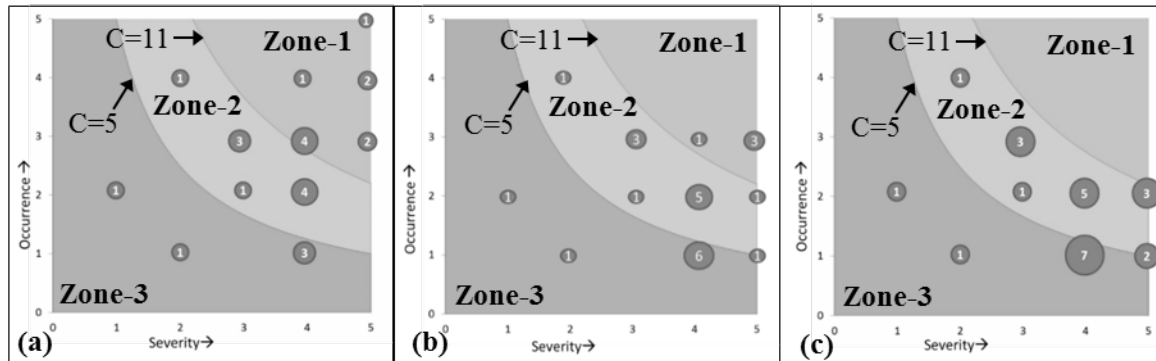


Figure 3 (a) Occurrence vs. Severity (b) after step-1 actions (c) after step-2 actions.

5. Present Status

The project of ITER CD and CL is moving ahead with the industrial partners. One prototype CL, made by INOX India Limited has been designed, manufactured, installed at the test facility and tested for its performance for thermal and mechanical integrity. The safety test that is, 'Break of Insulation Vacuum' has been successfully conducted without any failure [7]. Figure 4(a) and 4(b) shows sections while manufacturing as well as in as installed condition at the test facility.

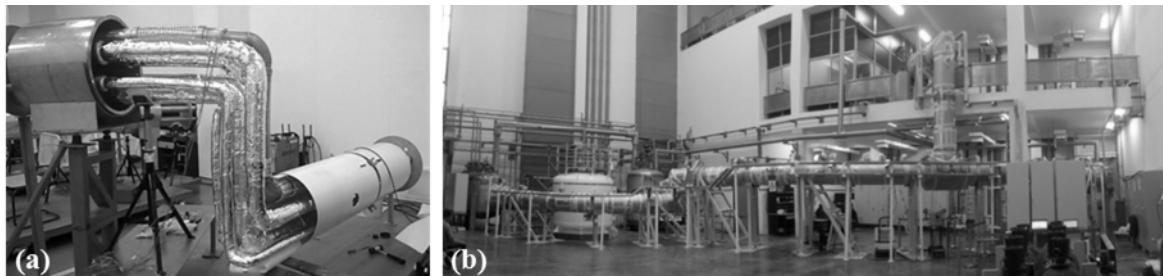


Figure 4 (a) PTCL element during fabrication at M/s Inox, (b) PTCL installed at ITER-India Cryogenic Laboratory.

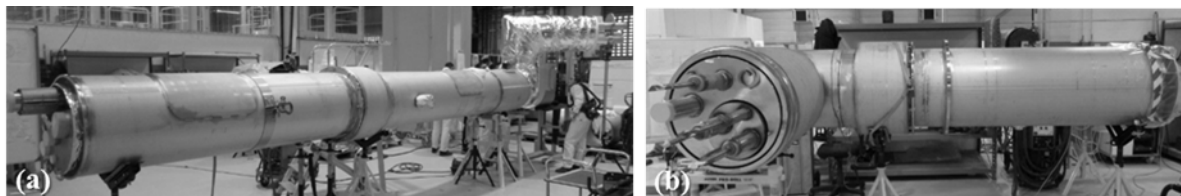


Figure 5 (a) PTCL element #1 at ALAT (b) PTCL element #2 at ALAT.

The design of the other prototype CL, being made by ALAT, France with the identical specification has been completed and the manufacturing at factory is also nearly completed. Figure 5(a) and 5(b) shows the manufactured segments at ALAT factory. As per the project life cycle, the preliminary and final design of the 'Relief line' has been completed following the review. The manufacturing readiness is under preparation. This is one of the longest lines (1.6 km) having partly warm relief line among all the CLs. Figure 6(a) shows the flexibility analysis of the relief line as an

integrated system inside the Tokamak building. The preliminary design of all LN₂ CLs also has been completed along with its review. Figure 6(b) shows the segment of such lines. The preliminary design of one of the Torus and Cryostat CL from the Group X lot is also nearly completed and ready for the design review.

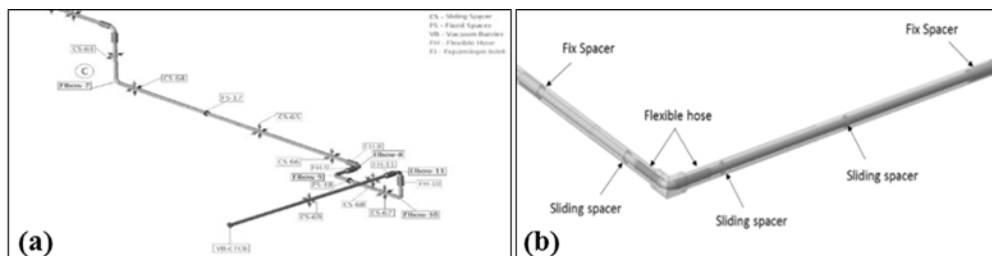


Figure 6 (a) CAESAR input file for flexibility analysis of typical segment of relief lines (b) Typical segment of LN₂ CL.

Two cold circulators have been designed and manufactured for the TF magnets of ITER. Figure 7(a) and (b) show them as designed. The performance tests have been completed, integrating both cold circulators in a Test-ACB. Figure 7(c) shows the integrated system with the test facility at Japan Atomic Energy Agency (JAEA) during the performance test [8].

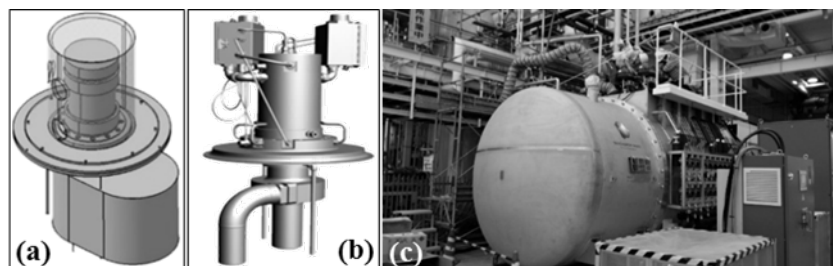


Figure 7 (a) Design cold circulator #1 (b) Design cold circulator #2 (c) Test-ACB installed at JAEA.

The preliminary design of the CTCB has been completed with due review, an important component of the CD system. The final design of the CTCB as well as the preliminary design of the ACBs is ongoing. Figure 8(a) shows a 3D view of the CTCB.

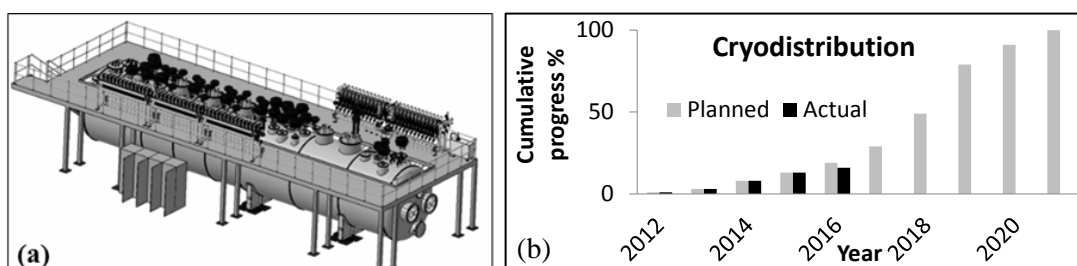


Figure 8 (a) 3D view of the CTCB (b) Progress of CD system.

A project level analysis for the cumulative progress has been conducted as per the INDA contractual schedule, satisfying the overall project need. Figure 8(b), Figure 9(a) and (b) show the projected cumulative progress as well as achieved cumulative progress in March 2016 for CD, Group X and Y CL.

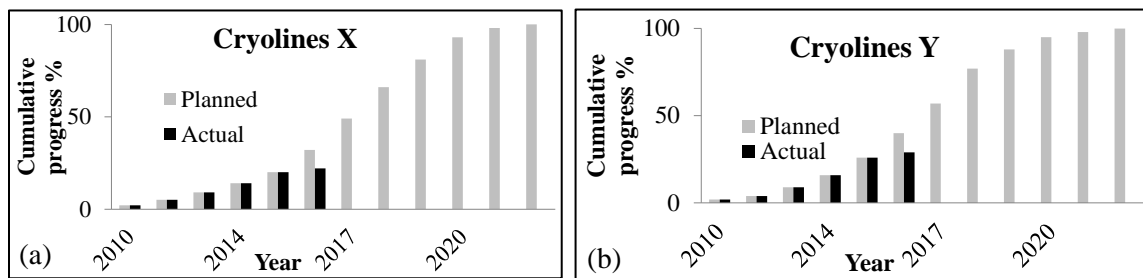


Figure 9 (a) Progress of Cryolines (X) group (b) Progress of Cryolines (Y) group.

6. Conclusions

The ITER Cryodistribution and Cryoline project of INDA is dynamically progressing to satisfy the overall ITER project objectives. After overcoming the initial teething problems both at technical and project management, the project took off, on the pathway of the strategy decided after the risk analysis. Interfaces remain as an issue for specific cases; however, it is being addressed on case to case basis, when the need arises. The project has completed an overall cumulative progress of approximately 29 % for Y-group of cryolines, 22 % for X-group of cryolines and 14 % for Cryodistribution system in March 2016 as per INDA contractual schedule.

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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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