

13 Cryoplant and Cryodistribution

13.1 Functions, Basis Configuration and System Boundaries

13.1.1 Functions

The fundamental function of the cryogenic system is to remove heat loads and maintain required operating temperatures for the ITER components that operate at cryogenic temperatures (see DRG1).

13.1.2 Configuration

The cryogenic system shall provide cooling at 4.5K of the following components; the superconducting magnet system, the 10 cryopumps of the torus primary vacuum system (in the divertor ports of the VV), three cryopumps of the neutral beam injector system (near the NB injectors), the two cryopumps installed inside the cryostat and two small cryogenic users, in particular the pellet fueling system (in a cask attached to the VV) and the ECH&CD gyrotrons (in the RF generator area of the tokamak complex).

The cryogenic system shall also provide cooling of the 80K thermal shields of the tokamak. A 80K helium loop shall be used for the active cooling of all the 80K thermal shields that are located inside the cryostat, the 80K chevron baffles and thermal shields of the cryopumps as well as all cryogenic lines of the ITER cryogenic system. The LN₂ subsystem shall be used for precooling the gaseous helium from 300K down to 80K as required for both the cooling cycle of the LHe plant and 80K helium loop of the thermal shields.

The cryogenic system is subdivided into three parts: the cryoplant, the cryodistribution and the system of the cryogenic lines.

The cryoplant includes the liquid helium (LHe) production plant, the liquid nitrogen (LN₂) production subsystem and the 80K helium loop. Equipment of the cryoplant is located in two buildings, in particular: the cryoplant compressor building and the cryoplant cold box building.

The cryoplant contains also liquid helium and liquid nitrogen tanks and 1.6-1.8 MPa pressure warm and cold helium storage. The warm and cold helium storage together with liquid nitrogen tanks are located, outdoor close to the cold box building.

The cryodistribution system consists of auxiliary cold boxes, in which cold circulating helium pumps (ACBs) and cold helium compressors (CCBs) are located, and cryoplant termination cold boxes (CTCBs). These ACBs, CTCBs and CCBs together with the LHe tanks are installed inside the tokamak building at the TCWS vault level.

The system of the cryogenic lines and manifolds is used to distribute liquid helium and 80K helium gas among the different components of the ITER machine. This system is distributed in various areas, in particular inside the tokamak building at three different levels, inside the cryoplant cold box building and in utility tunnels between the tokamak and the cryoplant buildings. The cryolines and signal lines in this system form closed cooling and control loops

for the ITER cryogenic system.

13.1.3 System Boundaries

The system boundaries with the cryogenic user systems are as follows:

- Coil termination boxes (CTBs) of the TF, PF plus CC coils and CS;
- Cold valve boxes (CVBs) of the magnet structure;
- CVBs of the 80K thermal shields of the tokamak;
- CVBs of the torus cryopumps, NB cryopumps and cryostat cryopumps;
- Cold boxes of the pellet injector units and ECH&CD gyrotrons.

All these CTBs and CVBs are located in the tokamak building at three different building levels, in particular: the basement level, the lower water pipe chase level and the upper CTB level (TCWS vault).

The interface (inlet/outlet of the all cryolines and manifolds) is located at the top (or bottom) of each CTB and CVB.

13.2 Specific System-Internal Requirements

13.2.1 Design

13.2.1.1 General

The design of the cryoplant shall be based on modular units to be consistent with the current manufacturing technology base. The modularity of the LHe plant shall allow operation in standby mode, while a failed module is being repaired. The cryogenic system shall be controllable and adjustable to allow operation at different heat loads between the maximum cooling demand of the reference plasma scenarios and reduced cooling requirements of the initial years of the plasma experiments.

The LHe plant shall be designed to allow operation in combined refrigeration and liquefaction mode. The refrigeration capacity is required for removing the refrigerating heat loads from the cryogenic components and liquefaction capacity is needed for cooling the current leads of the coils and for providing rapid cool-down of the torus cryopumps during their regeneration.

Two 80K cold boxes to cool the thermal shields shall be incorporated in the cryoplant. If one of these two 80K boxes fails the other box shall allow cooling the thermal shields. The total cooling capacity of the LN₂ subsystem for the 80K thermal shields should be chosen to satisfy both the nominal plasma pulsing and baking of the vacuum vessel.

A LHe tank shall be designed to allow accumulation of LHe during plasma operating periods with lower cooling demand, for using stored helium during subsequent plasma operating periods which require greater refrigeration capacity.

The LHe plant and LN₂ subsystem shall be designed to allow graduated decreasing of the helium temperature at the inlet of the magnet system during cool-down (as well as warm-up). The gradual cool-down is needed to guarantee acceptable mechanical stresses for the components of the magnet system during their cool-down from 300K to 80K. No additional

cryogenic equipment, except that for the nominal plasma pulsing and VV baking is foreseen for cool-down.

The cryogenic system shall be designed such that a quench or fast energy discharge from the magnet system does not lead to a large loss of helium to the atmosphere. The cryoplant shall have 1.6 - 1.8 MPa warm and cold tanks to store the total liquid helium inventory of all the cryogenic components of the ITER machine when both the machine and LHe plant are undergoing warm-up to 300K.

All cold boxes of the cryoplant and cryodistribution, and the cryolines shall be designed with devices for self-protection against overpressure.

13.2.1.2 Magnet System

A specific requirement for the cryodistribution system of the magnet system is the necessity to use cold helium circulating pumps. These helium pumps should be located in the auxiliary cold boxes (ACBs) of the cryodistribution system. Each individual cooling loop of the magnet system should contain two identical pumps for redundancy against pump failure. These ACBs should also contain heat exchangers of the supercritical helium flow and LHe baths of boiling helium to remove heat load from the magnet system.

For the magnet system the operating temperature of the LHe plant (temperature of boiling helium in the LHe baths) should be 4.3-4.4K. Cold helium vapour compressors should be included in the cryodistribution system to allow cooling at 4.3-4.4K that is below the operating temperature of 4.5K for standard refrigerators.

The ACB of the PF coils should be designed to allow installation of an additional cold compressor in order allow a redundancy for operating at 4.0-4.2K, in the event of the bypassing of one faulty coil pancake of the PF-1 or PF-6 coils.

The total refrigeration capacity of the LHe plant due to operation of the magnet system includes pulsed electromagnetic (AC/eddy current losses) and nuclear loads during plasma operation, static loads due to thermal radiation and conduction, heat generated by the operation of the liquid helium pumps and cold compressors. The AC/eddy current losses and nuclear heating are intrinsically pulsed heat loads and the cryodistribution system must be designed to smooth this pulsed heat load to allow steady-state operation of the LHe plant.

Large pulsed heat loads will also be generated in the magnet system as a result of a plasma disruption. The total cooling capacity of the LHe plant should be determined only by the normal operation heat loads without heat pulses related to plasma disruptions. This means it is acceptable to have an additional time interval between the nominal plasma pulses in order to restore the magnet system and LHe plant to continue with nominal plasma pulsing.

The LHe plant should also produce supercritical helium flow for cooling the current leads of the magnet system (liquefaction capacity). The current in the TF coils and the SHe mass flow rate to cool the TF current leads are kept constant during plasma pulsing. The current and heat loads on the current leads of the PF and correction coils and CS vary with the current scenario for each coil. Automatically controlled valves shall be installed at the outlets of all the current leads to allow adjustment of the SHe flow with current variation.

13.2.1.3 Torus Cryopumps

Six cryopumps will be initially installed in order to satisfy the pulsed plasma operational scenarios. For steady-state plasma operation, 4 additional cryopumps will be added to the 6 initially installed cryopumps.

During long-pulse plasma operation every 75 s one of the 6 pumps will be taken off-line for regeneration and another just-regenerated cryopump will be added to the set of 6 cryopumps. The 10 cryopumps allow continuous operation in such a way that at each moment of time the 6 cryopumps are pumping and 4 cryopumps are under the following 4 sequential stages of regeneration:

- cold helium exhaust from the cryopump for recovery cold helium by the LHe plant;
- warm-up of the cryopump from 4.5K to 80K plus gases desorption;
- pump-out of desorbed gases to the tritium plant;
- fast cool-down of the cryopump from 80K to 4.5K.

The design operating temperature of the LHe plant should be 4.5K. The LHe plant shall operate in a combined refrigeration-liquefaction mode. The refrigeration capacity is required for the nominal pumping by the 6 pumps and liquefaction capacity is needed for fast cool-down of one cryopump.

A helium circulating pump should be designed for forced-flow cooling the cryopumps.

Two cryopumps of the cryostat and the cryopumps of the neutral beam injector system are also included in the cooling loop of the torus cryopumps. The two cryopumps of the cryostat are used only during pump-down of the cryostat when the magnet system is warm and the heat load associated with operation of these cryopumps should not be added to the total capacity of the LHe plant.

13.2.1.4 Small Cryogenic Users

Small cryogenic users are the pellet fueling system and the ECH&CD gyrotrons. A total equivalent refrigeration capacity of about 0.7 kW is anticipated to cool these small cryogenic users.

13.2.1.5 80K Thermal Shields

An 80K flow of compressed helium shall be used for active cooling of all thermal shields of the ITER machine, in particular:

- cryostat (CTS), vacuum vessel (VVTS) and transition (TTS) thermal shields, which are located between the cryostat, the vacuum vessel (VV) and the magnet system, and around VV connecting ducts;
- gravity supports of the magnet system and VV (support thermal shields (STS));
- the 80K chevron baffles and thermal shields of the cryopumps;
- thermal shields of the all cryolines together with the auxiliary cold boxes.

Liquid nitrogen should be used for the precooling the gaseous helium down to 80K.

13.2.1.6 LN₂ Supply

The cryoplant shall have a re-liquefaction/refrigeration liquid nitrogen subsystem which includes LN₂ tanks. The re-liquefaction rate of the LN₂ subsystem shall be selected taking into account the following requirements:

- to precool gaseous He flow for the 80K thermal shields as described in section 13.2.1.5,
- to precool the gaseous helium down to 80K for the first cooling stage of the LHe plant to allow its normal operation,
- to precool gaseous He flow for gradual cool-down of the ITER machine,
- to supply an external He gas purification units.

13.2.1.7 He Purification

The capacity of a He purification system shall provide for the cleaning of gaseous He in the 1.6-1.8 MPa gas storage, the LHe plant, the magnet system and other ITER cryogenic components within 7 days before starting the initial cool-down of the ITER machine.

The capacity of purification equipment shall guarantee protection against frozen impurities inside the LHe plant heat exchangers taking into account that the ITER plant will remain cold for time periods of about 1 year.

13.2.1.8 Cryolines and Manifolds

In order to minimise the total number of the cryolines and manifolds inside the tokamak building, each cryoline of the coils shall include several cold tubes to provide for circulation with supercritical helium flow, to supply current leads, and to cool the 80K thermal shields of these lines.

The cryolines shall be designed to minimise the heat load to cryogenic tubes resulting from thermal radiation and conduction through the mechanical supports of the tubes and residual gas. The mass flow rate requirements for cool-down shall be taken into consideration in the selection of tube diameters.

13.2.2 **Operation**

The cryoplant will provide 100% availability for plasma pulsing in accordance with the ITER plasma operational plan. The maximum cooling demand of the cryoplant occurs during operation with the nominal plasma pulses (pulse repetition time of 1,800 s and burn time of 400 s).

The cryoplant must be operationally stable over a very wide range of plasma scenarios. The operational plan starts with protium plasma (minimum plasma operating demand) and then with deuterium and tritium plasmas at reduced requirements on the plasma current, duration of plasma burn and pulse repetition time. Each of these scenarios result in different heat loads for the LHe plant due to the neutron deposition and electromagnetic losses. The design of the cryoplant shall also allow operation with long pulse ITER plasma and “steady-state” plasma operation.

13.2.2.1 Vacuum

A vacuum of 10^{-3} to 10^{-4} Pa shall be maintained inside the auxiliary cold boxes and cryolines. The vacuum enclosure and internal pipes of the cryogenic lines and manifolds shall be designed such that leaks can be detected, localised and repaired within an acceptable time. Cryogenic boxes and cryolines shall be vacuum segmented where practical.

13.2.2.2 Water

The cryoplant and cryodistribution components (gas compressors, cold circulating pumps, cold turbines) which require water cooling supply shall be designed to operate with the following water conditions:

- Inlet temperature is 35°C;
- Pressure range is 0.4 to 0.5 MPa.

13.2.2.3 Electrical

The warm gas compressors of the cryoplant shall be supplied from the class 4 electric power supply (see DRG1).

The cold helium circulating pumps, cold compressors, and their local control and instrumentation shall be supplied from the class 4 electric power supply. The class 3 power (see DRG 1-uninterruptable) for the cold pumps and compressors should be used to allow continued cooling of the TF coils during 30 minutes of a slow energy discharge (no quench), when there is a loss of the class 4 electrical power to the cryogenic system.

13.2.2.4 Seismic

The cryogenic system shall be designed to withstand without damage SL-0 (see DRG1) earthquakes with 0.05 g peak horizontal and vertical ground acceleration.

13.2.3 Other

13.2.3.1 Assembly

The cryogenic system shall be designed to allow assembly consistent with the ITER construction schedule. The design of the cryoplant shall be based on modular units to be consistent with the current manufacturing technology base and allow maximum pretesting in the manufacturer's shops, thereby minimising the assembly and testing time at the ITER site.

13.2.3.2 Testing

The cryogenic system shall be designed to permit pressure and vacuum leak testing during initial assembly and for periodic tests, to diagnose malfunction or to satisfy statutory requirements prevailing at the ITER site.

Factory tests

Certain components of the cryoplant and system will be completed at the manufacturer's site and the following tests should be performed at the factory:

- dimension check;
- leak/vacuum test;
- pressure test;
- capacity test (where applicable).

ITER site tests

The following acceptance tests shall be performed at the ITER site after installation:

- control system and interlock tests;
- tests of protection;
- cold tests of the cryoplant components on dummy loads;
- integrated leak and cold capacity tests.

The site tests will be done accordingly to the site test procedure that shall be prepared by the supplier and approved by ITER site.

Dummy loads

Dummy for allowing cold tests of the cryoplant components shall be designed by the supplier and approved by ITER.

13.2.3.3 Instrumentation and Control

ITER will have a central control room for the overall site command control and data acquisition (CODAC) system. The ITER cryogenic system has its own local control system that shall be supplied by the cryoplant supplier. To install CODAC and interface with many ITER subsystems, ITER intends to place a contract with a special contractor to develop CODAC. CODAC is structured in a hierarchy composed of the supervisory control system and individual dedicated control subsystems to ensure the integrated control of the whole ITER plant.

The supplier shall provide local control cubicles (LCCs) for the cryoplant. The main functions of LCCs are:

- real time operation control and monitoring;
- emergency operation requests;
- personnel safety interlocks.

The LCCs shall allow the performance of all the necessary functions to operate the cryogenic system and its individual components. The operation of the subsystem/components “in local” will be organised according to “state machine” logic. Information from the data available to the LCC, shall be transferred to CODAC to allow the correct operation of the subsystem in “remote”. A local to remote change-over switch shall allow transferring control of the subsystem from its LCCs to CODAC.

The definition of the logic to be used in the LCCs is the responsibility of the supplier. Two groups of logic can be identified:

- the logic directly related to the equipment to be supplied;
- the logic dealing with all interface aspects with the rest of the ITER plant, through CODAC;

The development of software is the responsibility of the supplier.

Commissioning of the subsystem/components with its LCCs is part of the responsibility of the supplier, including commissioning of the signals to be exchanged between the LCCs and CODAC cubicles.

13.2.3.4 Mechanical

All cryogenic components shall be designed to protect against excessive mechanical stresses due to different material thermal contractions during cool-down.

13.2.3.5 Material

The reference material for the cold vessels and piping operated at high vacuum is type 304 L stainless steel, except for gas heat exchangers which are aluminium. The cryogenic system construction materials shall be suitable for liquid helium service.

13.2.4 Maintenance Considerations

Maintenance of the cryoplant and cryodistribution shall be based on the industrial proven experience for conventional cryogenic equipment.

To the maximum extent practicable, the cold process boxes and cryolines shall be designed to allow hands-on maintenance access to the internal cryogenic tubes and other cryogenic components such that detection and timely repairs can be made when required.

13.2.5 Surveillance and In-Service Inspection

Major surveillance and service inspection requirements are the following:

- vacuum leakage;
- impurity of gaseous helium/nitrogen;
- loss of helium/nitrogen from the cryoplant to atmosphere;
- integrity inspection of the high pressure vessels.

13.3 Codes and Standards

Industrial codes and standards of proven technology should be used for the design, the manufacture, the installation, the testing and operation of the cryoplant and cryodistribution. The cryogenic system shall be designed, procured, assembled, commissioned and maintained in accordance with the ITER vacuum design manual.

The component of the cryoplant and cryodistribution can be designed in accordance with the following codes:

Components	Codes
Warm/vacuum vessels of cold process boxes	ASME section VIII
Cryogenic helium and nitrogen heat exchangers	ASME section VIII
1.6-1.8 MPa vessels	ASME section VIII div.2
Warm and cryogenic piping	ASME sections B31.3 cat.M
Conventional warm and cryogenic valves	ASME section B16.34
Conventional warm gas compressors	ASME section VIII
Cold helium pumps and compressors	ASME section B73.1 M-2 M
Conventional LHe and LN2 tanks	ASME section VIII

The reference design code for pressure retaining elements is ASME section VIII, div.2 (pressure vessels). Other codes of the host or the supplier country that are similar to those selected can be also used.