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Conf-910968--27

UCRL- JC-107255
PREPRINT

NOV 01 1991

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THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

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This paper was prepared for submittal to
14th Symposium on Fusion Engineering
San Diego, CA
September 30 - October 3, 1991

September 25, 1991

Lawrence
Livermore
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A CRYOGENIC SYSTEM DESIGN FOR THE INTERNATIONAL
THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

UCRL-JC--107255

DE92 002162

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Abstract

A conceptual design for ITER was completed last year. The author developed a suitable cryogenic system for ITER as part of this conceptual design effort. An overview of the design is reported. Emphasis is on the fact that cryogenics is a mature science, and a system supporting ITER needs can be made from time-proven components without loss of efficiency or reliability. Because of the large size of the ITER cryogenic system, large numbers of compressors and expanders must be used. Very high reliability is assured by arranging these components in parallel banks where servicing of individual components can be done without interruption of operations. This and other ideas based on the author's experience with Mirror Fusion Test Facility (MFTF) operations are described.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Introduction

Presented is a design for an ITER cryogenic plant and cryogenic services. It is based on ITER design as of about May 1990, as described in Refs. 1-5. The main theme here is that ITER cryogenic requirements can be met using only time-proven equipment and system design. Additionally, the large size of the ITER cryogenic system permits efficient use of many parallel components, such as compressors and expanders. This should result in a much higher system reliability, since failure of one or two components will not greatly reduce system capacity and repairs can be made while the system continues to operate. It is a workable, somewhat optimized design supporting all the ITER PF magnets, TF magnets, and structure cooling requirements. The cryogenic plant compressors are used to force-flow 4.5 K helium to the ITER core. No cold pumps are used. The design satisfies cooldown requirements; reliability requirements; safety requirements, including quench-vent systems; cryogenic load requirements, including neutron heating, ac heating, thermal radiation etc.; and the problem of radiation carry-over by cryogens. Facilities floor plans are included. Supporting calculations for numbers given in this paper are included in Ref. 1. Subsequent, more rigorous analysis may result in some adjustments to the system design, but piping and component sizing, system capacities, etc. will probably not change greatly.

Cryogenic Loads

Total ITER load used is about 75.5 kW at 4.5 K. This assumes 500-s cycles of the reference Physics Phase scenario repeated continuously with negligible pauses between them. It also assumes that no intermediate temperature shielding is used and that 4.5 K surfaces are shielded from room-temperature radiation by 30 or 40 layers of multilayer insulation (MLI) in a 1-cm thick pack. This permits a minimum use of space in the ITER

core for cryogenic insulation. Use of 50 to 120 K shields on about two-thirds of the 4.5 K surfaces would reduce the 4.5 K heat load only by about 2.4 kW. The cost of accepting the additional 2.4 kW load might be negligible in comparison to the savings in complexity, added helium circuits, and extra space required by cooled shielding. Consequently, actively cooled shielding is not used in this design. Average nuclear and ac-loss heating used here are given in Table 1 below. Transient effects of peak nuclear and ac heating on coil temperatures and the refrigeration plant are considered in the next section.

Table 1. Heat Loads at 4.5 K

Room-temperature radiation load	6 kW
Support conduction load	4
Helium-gas-cooled current leads	10
Neutron heating (average) ²	22
PF-coil ac heating ²	10
PF-structure ac heating (average) ³	4
TF-case ac heating (split case, average) ³	8
TF-coil ac heating ²	3.5
Structure ac heating ³	8
Total 4.5 K load—average for continuous 500 s cycles	75.5 kW

Standby Loads

Inspection of Table 1 shows the standby loads are: room-temperature radiation, support conduction, and gas-cooled lead loads. The remaining loads in Table 1 occur only during a burn cycle. Thus, the standby loads total 20 kW. This still represents a considerable electrical load (about 6.3 MW).

Effects of AC and Neutron Transient Heating

The majority of neutron heat is adsorbed by the toroidal field (TF) case and coil turns closest to the plasma. Neutron heating in the poloidal field (PF) coils is negligible. Neutron heating is fairly constant for the 200-s burn time (between 90 and 290 s during the 500-s pulse). Dwell time of helium in the TF-coil first turn is about 120 s for this point design. Since dwell time in the first turn is less than burn time, the critical first-turn temperature will approach a steady-state value. Here we conservatively calculate TF-coil temperature as if neutron heating is continuous, since the first and second critical turns do approach steady state.

**TF-Coil Temperature Profile from Neutron
and AC Heating**

TF-coil temperature profiles resulting from neutron heat do not exceed 6.0 K. Thus a comfortable temperature spread is maintained between operating temperature and current-sharing temperature.

Significant ac heating occurs in the TF-coil cases (as shown in Ref. 3), and this heating is more or less divided between the first 90 s and last 210 s of the cycle.

Calculations show that the thermal mass of helium in the TF-case flow paths will adsorb this transient heating with about a 0.2-K temperature rise. Calculations show this case-temperature rise should not significantly affect TF-coil temperature, thus transient effects of ac heating to the TF cases are not a problem. However, spatial distribution of the ac heating in the cases has yet to be determined. If heating is concentrated in certain areas of the cases, additional helium volume may be required to handle it.

The ac heating in the outer inter-coil structure is about the same as in the TF cases and can be handled by similar, modest volumes in helium flow paths. Coil structures between TF coils would require about 8.6 kg (60 L) of helium to adsorb transient ac heating with a 0.2 K rise. Structure flow paths should easily provide this volume.

The ac heating in the CS structure is about half that in the TF cases. Analysis of transient effect here is not done yet, but appears to be no problem.

The ac heating in the outer PF coils and their structures and in the TF coils has not been considered here.

When the flow reaches the TF-coil case (after flowing through the coil), the pressure is about 0.3 MPa in this design. Consequently, JT cooling occurs in the case. This limits case temperature to about 6.0 K, so heat transfer from the case to the coil is minimized.

Cooldown

Cooldown procedure is presented in Ref. 1. Calculations show cooldown time from room temperature to operating temperatures is 345 hours.

Facility Layout

Figure 1 shows a plan view of the ITER core, power-supply building, and cryogenic building. One myth that is dispelled here is that the cryogenic building needs to be close to the ITER core. Calculations show the cryogenic facility and refrigerators can be located several hundred meters from the ITER core without serious losses. This is a result of the system's large capacity and high delivery pressures associated with the forced-flow concept. This permits a convenient and centralized layout of cryogenic equipment and minimal space requirements at the ITER core. The power-supply building is located next to, or is part of, the reactor building to reduce required lengths of superconducting bus leads. A service tunnel houses 250-mm piping that carries 4.5-K helium to and from ITER.

Magnet Quench

During a quench, peak pressures near the center of a TF-coil, 400-m-long flow path can reach 40 MPa.⁴ This occurs about 20 s after quench initiation, assuming the magnets were not dumped and all magnets quenched simultaneously. Flow resistance of the CICC conductor limits flow rate from the magnets to modest values. Pressures developed in the coil leads, supply piping, and quench vent piping are lower than their rated pressure under these extreme conditions. The larger piping (300 and 400 mm, shown in Fig. 2) between the reactor and the vent stacks is required to handle quench flows without exceeding the 2.0 MPa pipe pressure rating.

It is recommended that helium during a quench be released to the atmosphere unless concerns about release of radioactive material cannot be satisfactorily solved. Capital cost of recovery equipment for this volume of helium is not justified on the basis of possible loss of helium.

Radiation Carry-Over by Cryogenic Helium

Two areas of concern exist: first, radiation carried via the helium to the power supply and cryogenic buildings during normal operation; second, carryover to the atmosphere by vented helium during a quench or other fault condition. This appears to be a solvable problem, but requires more investigation. Helium itself cannot activate; helium at 4.5 K is extremely pure, since all other materials freeze out above this temperature. However, particles of frozen gases and solid matter, such as welding slag, could be carried along by the helium. A solution is to use filters in helium flow paths to and from the ITER reactor. Substantial filters with perhaps a 0.5–5 micron rating could be easily incorporated in helium lines. Filters designed with higher than required pressure rating and flow capacities would ensure extreme reliability of this component.

Refrigeration System

Reference 5 describes the refrigerator system. Ref. 5 shows the refrigerator schematic. A full analysis of the refrigerator cycle was done and operating parameters, efficiencies, component specifications, etc. are presented in the tables of Ref. 5. The analysis used turbine efficiencies of around 60%, and this resulted in an overall efficiency of 342 W per W (electrical input watts to watts at 4.5 K). Actual turbine efficiencies will be better (70 to 80%, as quoted by a manufacturer), and this will result in an overall efficiency of about 310 W per W. The 100 kW refrigerator can be made up of four 25 kW cold boxes supported by banks of paralleled compressors, as shown in Fig. 3, without affecting cycle parameters given in Ref. 5. This would provide a maximum of reliability since ITER could be sustained at full operation with any three of the four cold boxes and any 75% of the compressors in operation. In stand-by mode with full current in the magnets, it could be easily sustained by one of the four cold boxes. Common supply and discharge headers for each stage of compression and isolation valves for each compressor permit repairs on individual compressor skids during operation. This is shown in Fig. 3. Reference 5 shows a similar valving arrangement for oil-removal systems and turbines to permit in-operation repairs. As noted under the distribution or helium services section of this paper, helium supply required for this point design is 4.2 kg/s at 0.8 MPa and 4.5 K. By bypassing the number three turbine, supply pressure can be increased up to 2.0 MPa with some cost in efficiency and overall capacity (the 100 kW would be reduced to about 75 kW). Higher supply pressures provide a capability of forcing more flow through the coils and removing more heat if required by subsequent ITER design changes.

The 60,000-L dewar, shown schematically in Ref. 5, contains two heat exchangers. The exchanger in the supply line cools helium going to the ITER loads to 4.5 K. The exchanger in the return line cools helium to saturated liquid temperature before it enters the return path in the cold box. Thus the 60,000 L of liquid helium serves as a thermal mass to average out-load fluctuations at ITER and provide a stable return temperature required by the refrigerator.

*Handles high quench flow

Figure 2. Quench/Vent Related Component and Circuits

Figure 3. ITER Refrigeration Plant

Nomenclature

Figure 1

1. Cryogenic plant building is shown to scale.
2. The distance between the cryogenic building and reactor can be large (up to ~200 m) since cryogenic losses in this length piping are small and temperature rise in the cryogenic supply line is less than 0.03 K.
3. The power-supply building houses a centrally located lead box with all the vapor-cooled leads. This reduces the lengths of 40-kA copper busses.
4. A separate 4.5-K helium-filled duct houses superconducting leads between the power-supply building and reactor building.
5. Helium-supply control-valve alcove.

Figure 2

1. Line sizes shown are required to handle maximum or worse-case quench-vent rates. Quench-vent calculations are conservative and are presented in Ref. 4.
2. HEPA filters (perhaps 1 micron) are sized to easily handle maximum possible quench vent rates. Their purpose is to block any solid or frozen particles that may be activated.
3. The reverse-flow bypass check valves permit high vent rates associated with quenches. They bypass the flow orifices, filters, and valves that have too much flow resistance for quench flows.
4. Quench vent stacks Tee off the main helium supply and return lines.
5. The supply-line check valve prevents quench-vent pressures from backing into the heat-exchanger dewar and refrigerators.
6. The bypass valve prevents pressure build up in the dewar and refrigerator systems in the event the flow is stopped by a quench condition.
7. The return-line shut-off prevents quench-vent pressures from backing into the refrigerator system. This could be activated by flow stoppage, pressure rise, or quench detection.

Figure 3

1. Cryogenic plant building is shown including dimensions.
2. Individual compressor skids are shown to scale for 100-kW plant, assuming an extra skid in each stage for redundancy and maintenance.

3. Each compressor skid can be isolated during ITER operation for maintenance or repair.
4. Dual oil separators and freeze out units are shown to scale.
5. Four identical 25-kW refrigerator cold boxes are shown to scale. In full operation, ITER can operate with three of the four cold boxes. In stand-by, only one cold box is required.
6. Piping shown permits use of any combination of compressor skids with any or all cold boxes. This greatly enhances reliability.
7. The heat exchanger dewar is shown to scale; Ref. 3 shows the schematic of compressors, cold boxes, and dewar.
8. Liquid nitrogen may be used to improve cooldown time and/or shield cooling. Liquid nitrogen could be confined to the cryogenic building, and cooling accomplished by LN/He heat exchangers.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References

1. D. S. Slack, Internal Correspondence, SCMDG 90-5.1-24, June 27, 1990.
2. J. R. Miller, Correspondence to N. Mitchell, SCMDG 90-5.4-15, April 11, 1990.
3. J. R. Miller, Correspondence to A. Kostenko et al., *Baseline Eddy-Current Heating in Structures for Cryo-System Analyses*. May 9, 1990.
4. D. S. Slack, *Analysis of Quench-vent Pressures for Present Design of ITER TF Coils*, presented at the 13th Symp. on Fusion Eng, Knoxville, TN, October 2-6, 1989.
5. D. S. Slack, *Recommendations for a Cryogenic System for ITER*, presented at the 13th Symp. on Fusion Eng, Knoxville, TN, October 2-6, 1989.

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