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Safety Analysis Results for Cryostat Ingress Accidents in ITER[a]

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Abstract

Accidents involving the ingress of air or water into the cryostat of the International Thermonuclear Experimental Reactor (ITER) tokamak design have been analyzed with a modified version of the MELCOR code for the ITER Non-site Specific Safety Report (NSSR-1). The air ingress accident is the result of a postulated breach of the cryostat boundary into an adjoining room. MELCOR results for this accident demonstrate that the condensed air mass and increased heat loads are not a magnet safety concern, but that the partial vacuum in the adjoining room must be accommodated in the building design. The water ingress accident is the result of a postulated magnet arc that results in melting of a Primary Heat Transport System (PHTS) coolant pipe, discharging PHTS water and PHTS water activated corrosion products and HTO into the cryostat. MELCOR results for this accident demonstrate that the condensed water mass and increased heat loads are not a magnet safety concern, that the cryostat pressure remains below design limits, and that the corrosion product and HTO releases are well within the ITER release limits.

1. Introduction

The cryostat is the secondary confinement barrier for in-vessel inventories in the International Thermonuclear Experimental Reactor (ITER) design. To investigate the robustness of this confinement barrier, unlikely (frequency $1x10^{-2}$/a to $1x10^{-4}$/a) and extremely unlikely (frequency between $1x10^{-4}$ to 1x10-6/a) events that cause the ingress of air and water into the cryostat were examined for the ITER Non-site Specific Safety Report - 1 (NSSR-1).[1] The postulated air ingress accident results from a breach in the cryostat boundary. Since the cold magnet structures of the cryostat act as cryosorption surfaces, the air that enters the cryostat will condense and form air-ice on these surfaces. The consequences are increased heat and weight to magnets and a partial vacuum developing in adjoining rooms of the ITER facility. It has also been postulated that a toroidal field (TF) magnet could experience an electrical insulation fault that results in an intense electrical arc. Although the arc's electrical energy would be limited by ground resistors, it is assumed that sufficient energy is available to melt a helium cooling line from the TF coil, a Primary Heat Transport System (PHTS) guard pipe, and the PHTS coolant pipe within the guard pipe. This accident discharges PHTS water, TF coil helium, and the PHTS water activated corrosion products and HTO into the cryostat.

These accidents have been analyzed with a modified version of the MELCOR code.[2,3,4] In Section 2 we describe the results of the cryostat air ingress accident. In Section 3, we present the results for the cryostat water and helium ingress accident. Finally, Section 4 summarizes the safety significance of these results and presents conclusions we have drawn for the ITER design from this study.

2. Cryostat air ingress accident analysis

The sub-sections that follow describe the accident scenario examined, the method of analysis used, and thermal-hydraulic results obtained for the cryostat air ingress accident.

2.1 Accident description

The postulated accident is a breach of the cryostat boundary so that air from an adjoining room (the equatorial pit room which is 10,000 m^3 in volume) enters the cryostat. The cross sectional area of air ingress is 0.01 m^2, postulated to be the result of a material failure, such as a long crack in a weld or a metal bellows failure at a cryostat penetration. Detection of the leak will trigger a plasma shutdown of 60 seconds duration (slow train of the Fusion Safety Shutdown System (FSSS)), and then a magnet shutdown of an additional 15 seconds duration. The vacuum vessel is intact in this event, and has all cooling loops functioning to protect in-vessel radioactive inventories and remove decay heat. The 15-second fast discharge of the toroidal field (TF) magnet coils will raise their temperature to about 55 K. These small breaches can threaten the integrity of the magnet systems by foreign material admission that can allow arcing, and by condensed gas accumulation on the magnet surfaces thereby increasing the magnet weight by large amounts.

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Listed below are all safety relevant systems and parameters for this accident:

- cryostat vessel design pressure is 0.2 MPa
- the TF coils fast discharge, raising their temperature up to 55 K
- slow train of the FSSS (60 second shutdown)
- vacuum vessel and its cooling systems are intact; there is no release of radioactive materials from the vacuum vessel
- cold structures in the cryostat serve as natural cryosorption surfaces, pumping the air and forming ice on their surfaces
- after 24 hours, the air ingress is assumed to be reversed by operator actions.

2.2 Method of analysis

A modified version of the MELCOR code was used for this analysis.[2,3,4] This version of MELCOR has air as a fluid instead of water. The MELCOR code was used to calculate the resulting air flow, pressures and temperatures in the cryostat and equatorial pit. Air leakage from the environment into the cryostat and the equatorial pit were modeled, including a ventilation duct between the equatorial pit and the environment. MELCOR was also used to calculate structure temperatures inside of the cryostat and air condensation on these structures.

For this accident scenario, the thermal behavior of the TF coil cases, TF coil support structures, PF coils, vacuum vessel (VV), VV thermal shields, cryostat walls, and cryostat thermal shields was simulated.[5] The thermal resistance of the thermal shields was modeled as radiant heat transfer past ten foils, and was allowed to degrade when air enters the cryostat by including the effect of conduction between foils and convection at the surface of the thermal shields. The required helium cooling rate for the cryostat thermal shields to maintain the inside surface design temperature of 80 K was determined to be about 37 kW, while that for the vacuum vessel shields was approximately 40 kW. This cooling rate was maintained during the accident analysis. Radiant heat transfer between the thermal shields and the TF coil cases was included in the model. To maintain the TF coil cases at operating temperatures in the range of 4 to 5 K, a cooling rate of 1.7 kW was imposed on the inner surface of the TF coil case as a boundary condition. This cooling was also maintained during the course of the accident analysis. All thermal properties were extended down to cryogenic temperatures for this analysis.[5]

It was assumed for this analysis that TF coil discharge would occur 60 seconds after either one of two events happened. The first was a low pressure in the equatorial pit (0.09 MPa). The second was a high temperature on the inside surface of the TF coil case (assumed to be 20 K). The TF coil discharge was simulated by adding 10.5 GJ of energy to the coil case in 15 seconds. This energy results in a 55 K increase in TF coil case temperature when starting from an initial temperature of 4 K.

2.3 Transient analysis results

The following results are shown in Figure 1 for this accident:

- cryostat and equatorial pit pressure
- field coil, coil support, and cryostat wall temperatures
- condensed air mass on field coils and coil supports
- total condensed air mass
- equatorial pit leak and ventilation duct mass flows.

The cryostat pressurizes only slightly during the first 3000 seconds of this accident. This slight pressurization is due to the magnets cryopumping the air that enters the 0.01 m^2 breach between the cryostat and the equatorial pit. After 3000 seconds, the pressure in the cryostat rises to a maximum value of 0.105 MPa by 6.7 hours, when the cryostat pressure exceeds the equatorial pit pressure causing air to flow back into the equatorial pit. The equatorial pit pressure dropped below 0.09 MPa at 950 seconds and continued to drop until a minimum pressure of 0.084 MPa was reached by 2.6 hours. This pressure then returns to atmospheric values by 5.6 hours. While the cryostat pressure is well below the design limit of 0.2 MPa, the equatorial pit pressure did drop slightly below the lower design limit pressure of 0.09 MPa.

As the air enters the cryostat it condenses on the TF and PF coil structures causing these structures to heat up. The TF coils discharge at 1010 seconds (i.e., 950 seconds when equatorial pit low pressure signals occurred plus 60 seconds for the FSSS shutdown) resulting in rapid rise in the TF coils surface temperature. As air continues to fill the cryostat, convective heat transfer with the cryostat walls causes a gradual rise in TF coil case, PF coil, and thermal shield temperatures and the decrease in cryostat wall temperature to a minimum of 280 K. There has also been a degradation of the thermal resistance of the thermal shield as a result of gas conduction across the gaps between the foils of the thermal shield. By 24 hours, the TF coil case, PF coils, and thermal shields have reached temperatures of 197 K, 225 K, 285 K, respectively. The cryostat wall temperature has returned to 297 K by 24 hours.

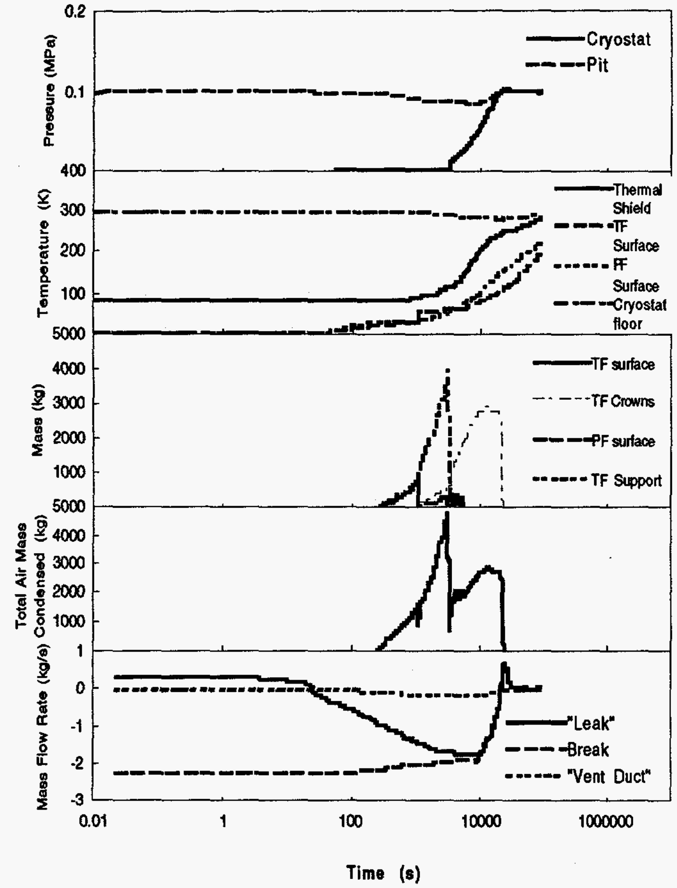

Figure 1. Thermal-hydraulic analysis results for the cryostat air ingress accident scenario.

The maximum air mass condensed on the TF coils, PF coils, TF intercoil support, and upper and lower TF coil crowns was calculated to be 850, 310, 4000, and 2890 kg at times of 980, 2830, 2860, and 13,170 seconds, respectively. By 5600 seconds, all structures have reached temperatures that are in excess of the air freezing temperature, except the upper and lower crowns. These structures have the lowest surface area to volume ratio of the structures modeled. As a consequence, these crowns remain cold and continue to cryopump the air entering the cryostat for about 6.6 hours before exceeding the freezing temperature of air. The total condensed mass reached a maximum of 4810 kg at 3060 seconds, decreased to 2000 kg at 1 hour, then increased again to 2890 kg by 3.7 hours.

The calculated leak mass flow rate into the equatorial pit exceeds that of the ventilation duct by an order of magnitude, that is 1.7 kg/s and 0.16 kg/s for the leak and duct, respectively. However, a flow rate of 0.16 kg/s in a duct the size of the ventilation duct (cross-sectional area of 10 cm^2)[5] results in a air velocity of approximately 130 m/s. The maximum break mass flow rate and velocity were 2.2 kg/s and 190 m/s, respectively. The maximum air mass to enter the cryostat was 29,610 kg by 5.8 hours.

3. Cryostat water and helium ingress accident

The sub-sections that follow describe the accident scenario examined, the method of analysis used, and the thermal-hydraulic and aerosol transport results obtained for the cryostat water and helium ingress accident.

3.1 Accident description

During a plasma pulse, a toroidal field (TF) magnet experiences an over-voltage condition or an electrical insulation fault that results in an intense electrical arc. Although the arc's electrical energy would be limited by ground resistors, it is assumed that sufficient energy is available to melt a helium cooling line from the TF coil, a Primary Heat Transport System (PHTS) guard pipe, and the PHTS coolant pipe within the guard pipe. For this calculation, the coolant and guard pipes are assumed to suffer breaches equivalent to double ended guillotine breaks (DEGBs). The pump for the affected coolant loop of the PHTS is assumed to quickly trip when the water pressure at the pump inlet reaches saturation conditions, to prevent cavitation damage and to slow the coolant flow out of the break location. The pressure difference between the cryostat (1E-04 Pa) to the coolant pipe pressure (4 MPa) causes the coolant to blow down as a steam/water mixture into the cryostat. The magnet damage from the arc event includes a breach of the magnet cooling lines, releasing 4 K helium coolant from half of the TF magnet coils at a spill rate of 30 kg/s for 200 s.[1] This helium vents into the cryostat. The magnet coils are discharged by the magnet fast discharge system (15 seconds), terminating the arc when sufficient energy has been dissipated in the magnet discharge system resistors. The plasma pulse is naturally terminated in a disruption as the magnetic fields dissipate.

This postulated event was selected as a reference accident since it envelopes all types of smaller cooling fluid breaches into the cryostat vessel. These breaches can threaten the integrity of the magnet systems by foreign material admission that can allow further arcing, and by condensed gas accumulation on the magnet surfaces thereby increasing the magnet weight.

Listed below are all safety relevant systems and parameters for this accident:

- cryostat vessel design pressure is 0.2 MPa
- the TF coils fast discharge, raising their temperature up to 55 K
- cold structures in the cryostat serve as natural cryosorption surfaces, pumping the steam and forming ice on their surfaces

- after 24 hours, the coolant ingress is assumed to be reversed by operator actions.

3.2 Method of analysis

A modified version of the MELCOR code was used for this analysis that allows for the treatment of temperatures below the triple point of water.[2,3,4] This MELCOR version was used to calculate the resulting coolant flow, pressure, and temperatures within the cryostat, and FW/shield primary heat transport system (PHTS). MELCOR was also used to calculate structure temperatures of cryostat, magnet structures and FW/shield components and the condensation of water or air on these structures.

For this accident scenario, the thermal behavior of the TF coil cases and support structure, PF coils, vacuum vessel (VV), VV thermal shields, cryostat walls, and cryostat thermal shields was simulated as described in Section 2.2 of this paper. In addition, a helium pumping system was modeled in the cryostat for post-accident pressure recovery. The required helium pumping rate to achieve sub-atmospheric pressures in the cryostat within 32 hours was determined to be about 110 kg-He/hr.

The entire FW/shield PHTS for a single loop was modeled. This model included the FW/shield components and associated coolant volumes, the system coolant pipes, pump, pressurizer, and heat exchanger. The FW/shield PHTS was brought to a thermal equilibrium under full plasma power prior to the initiation of the accident. After plasma termination by a plasma disruption, the FW/shield component power was decreased to decay heating levels.[5] The failed pipe was assumed to be one of the outlet pipes of the PHTS leading back to the HTS vault. The water from this break discharged directly into the cryostat.

3.3 Transient analysis results

The following results are shown in Figure 2 for this accident:

- cryostat pressure
- cryostat atmosphere temperature
- TF and PF coil surface, thermal shield, and cryostat floor temperatures
- condensed water mass on field coils and coil supports
- FW/shield PHTS break mass flow rate

The cryostat pressure reaches a maximum value of 0.17 MPa in 180 seconds. After this time the cryostat pressure drops to 0.15 MPa by 1025 seconds. This pressure shows a second increase that reaches a maximum of 0.16 MPa by 3.8 hours. This second pressure rise is due to the heat up of structures in the cryostat by heat transfer from the environment, and is limited to 0.16 MPa by the emergency helium pumping system of the cryostat. By 29 hours sub-atmospheric pressures are obtained in the cryostat. These pressures are below the design limit pressure for the cryostat of 0.2 MPa for this accident.

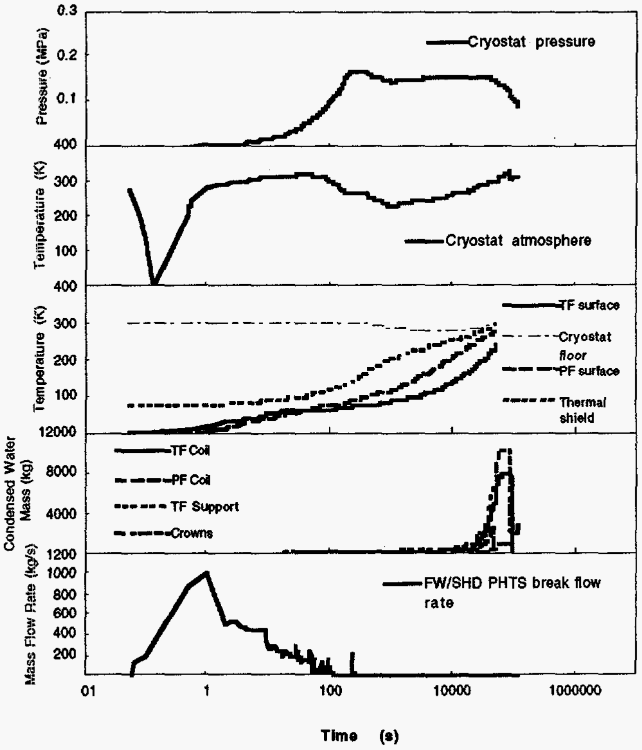

Figure 2. Thermal-hydraulic analysis results for the cryostat water and helium ingress accident scenario.

The temperature of the steam/helium atmosphere that develops in the cryostat during this accident drops to a low of 240 K, even though the helium gas discharging from the broken magnet cooling line is at 4 K. This temperature illustrates that the steam rapidly heats the helium. The cryostat atmosphere shows a gradual heating over the remainder of the accident, with some fluctuations when ice melts from the magnets. The magnitude of these fluctuations should not be given much credence due to the level of detail of the MELCOR model. As water enters the cryostat it condenses on the TF and PF coil structures, causing these structures to rapidly heat up. The TF coil case surface initially heats up at 5 K/s, reaching 140 K by 3 hours. The PF coil surface heats up at 12 K/s, reaching 210 K by 3 hours. The thermal shield for the cryostat floor heats to 245 K in 2 hours, and reaches 255 K by 3 hours. The cryostat floor temperature drops to 275 K in 2 hours, then gradually returns to 300 K by 32 hours.

The maximum water mass condensed/frozen onto the TF coils, PF coils, TF intercoil support, and upper and lower crowns was calculated to be 7950, 2560, 10,215, and

3150 kg at times of 23.9, 12.3, 23.9, and 32 hours, respectively. The gradual increase in condensed mass is due to the evaporation of water that has pooled on the floor of the cryostat. By the time of the plateau that occurs after 16 hours most of the water in the pool has evaporated and re-condensed on cryostat structures. By 25 hours, all structures within the cryostat reach temperatures that are in excess of the water triple point value, except the upper and lower crowns. These structures have the lowest surface area to volume ratio of the structures modeled. As a consequence, these crowns remain cold and continue to cryopump the water over the entire course of the accident. The total condensed mass reached a maximum of 19,375 kg at 23.9 hours.

The calculated break mass flow rate peaked at a value of 1000 kg/s, then exponentially drops to near zero in 110 seconds once the FW/shield PHTS and cryostat reach a pressure equilibrium. After this point, steam slowly leaks from the PHTS into the cryostat as helium is pumped from the cryostat atmosphere.

Radioactive inventories mobilized in this event are the tritium in the form of the HTO (2.45 g) and activated corrosion products (51.4 g) in the water within the damaged PHTS loop, and any activated structural and insulation materials mobilized by the magnet arcing.

Steam condensation is considered in the analysis of HTO transport. Agglomeration and gravitational settling inside the cryostat are the only aerosol deposition mechanisms considered.[6] The cryostat is assumed to leak at 1%/day (at 1 atmosphere over-pressure). The releases are stacked after being filtered.

Table 1 summarizes the different components of mobilized radioactivity, its transport behavior in the facility, and the release to the environment. The results indicate that most of the tritium and corrosion products are trapped in the condensed/frozen water on the magnet surfaces. Some of the corrosion products are also deposited by gravitational settling on the cryostat floor.

4. Summary and Conclusions

In the event of an air ingress accident caused by an unlikely accident in the ITER cryostat, the reduction of air pressure in the equatorial pit room, down to 0.084 MPa from the typical value of 0.1 MPa, represents a design concern for room. Air will freeze onto the cold magnet surfaces inside the cryostat, but the accumulated weight of frozen air is less than 1.5 metric tons for each of the twenty toroidal magnet coils. This weight is much less than the magnet coil weight (over 400 metric tons per coil), and it is not expected to pose any threat to magnet structural integrity. No radioactivity release is involved in this accident scenario.

Table 1. Environmental release, transport and mobilized for a cryostat water and helium ingress event.

Environmental releases		
	HTO (g)	Corrosion Products (g)
stacked	5.16×10^{-4}	1.25×10^{-4}
ground	0.0	0.0
post accident	1.69×10^{-3}	4.62×10^{-5}
Deposited in Cryostat		
at 32 hours	0.0	3.58
Trapped in Liquid		
at 32 hours	3.5	47.9
Airborne in Cryostat		
at 32 hours	0.17	9.23×10^{-4}
Mobilized		
	2.45	51.4

In the event of a water and helium ingress accident caused by an extremely unlikely event, the combination of steam and helium non-condensable gas escaping into the cryostat raise its pressure up to roughly .15 MPa, but the cryostat is rated to 0.2 MPa absolute internal pressure. The steam condenses onto the magnets, reducing pressures but also adding roughly one metric ton of extra mass to each of the twenty toroidal field magnet coils. Since each of these coils weighs over 400 metric tons, the added weight is not expected to threaten structural integrity. The condensation reduces the HTO and the corrosion product releases from the cryostat. These releases are stacked by a nuclear-grade HVAC system resulting in very small releases that are well within ITER release limits.

Acknowledgment

This paper is an account of work undertaken within the framework of the ITER Engineering Design Activity (EDA) Agreement. Neither the ITER Director, the Parties to the ITER Agreement, the U.S. DOE, the U.S. Home Team Leader, the U.S. Home Team, the IAEA or any agency thereof, or any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the parties to the ITER EDA Agreement, the IAEA or any agency thereof.

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the Parties to the ITER Agreement, the U.S. DOE, the U.S. Home Team Leader, the U.S. Home Team, the IAEA or any agency thereof.

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