Safety issues and approach to meet the safety requirements in tokamak cooling water system of ITER

George Flanagan [a], Susana Reyes [b], K.P. Chang [b], Jan Berry [a], Seokho Kim [a,*]

[a] *US-ITER, ORNL, 1055 Commerce Park, Oak Ridge, TN 37830-6483, USA*
[b] *ITER Organization, CS 90 046, 13067 St Paul Lez Durance Cedex, France*

Abstract

The ITER (Latin for "the way") tokamak cooling water system (TCWS) consists of several separate systems to cool the major ITER components—the divertor/limiter, the first wall blanket, the neutral beam injector and the vacuum vessel. The ex-vessel part of the TCWS systems provides a confinement function for tritium and activated corrosion products in the cooling water. The Vacuum Vessel System also has a functional safety requirement regarding the residual heat removal from in-vessel components. A preliminary hazards assessment (PHA) was performed for a better understanding of the hazards, initiating events, and defense in depth mechanisms associated with the TCWS. The PHA was completed using the following steps. (1) *Hazard Identification*. Hazards associated with the TCWS were identified including radiological/chemical/ electromagnetic hazards and physical hazards (e.g., high voltage, high pressure, high temperature, falling objects). (2) *Hazard Categorization.* Hazards identified in step (1) were categorized as to their potential for harm to the workers, the public, and/or the environment. (3) *Hazard Evaluation*. The design was examined to determine initiating events that might occur and that could expose the public, environment, or workers to the hazard. In addition the system was examined to identify barriers that prevent exposure. Finally, consequences to the public or workers were qualitatively assessed, should the initiating event occur and one or more of the barriers fail. Frequency of occurrence of the initiating event and subsequent barrier failure was qualitatively estimated. (4) *Accident Analysis.* A preliminary hazards analysis was performed on the conceptual design of the TCWS. As the design progresses, a detailed accident analysis will be performed in the form of a failure modes and effects analysis.

[*]Corresponding author at: Oak Ridge National Laboratory, P.O. Box 2008, MS6483, Oak Ridge, TN 37831-6483, USA.
Tel.:00-1-865-241-1392/Fax: 00-1-865-574-8393.
E-mail address: kims@ornl.gov.

The results of the PHA indicated that the principal hazards associated with the TCWS were those associated with radiation. These were low compared to hazards associated with nuclear fission reactors and were limited to potential exposure to the on-site workers if appropriate protective actions were not used. However, the risk to the general public off-site was found to be negligible even under worst case accident conditions.

Key Words: Hazards analysis; Safety; Accident analysis; Tokamak cooling water system

1. Introduction

The ITER (Latin for "the way") tokamak cooling water system (TCWS) consists of four primary heat transfer systems: the divertor/limiter (DIV/LIM), the first wall blanket (FW/BLK), the vacuum vessel (VV) and the neutral beam injector (NBI).

A preliminary hazards assessment (PHA) was performed on the first three primary heat transport systems (PHTS) to gain a better understanding of the hazards, initiating events, and defense-in- depth mechanisms associated with the TCWS. Data for the NBI system were not available at the time of this analysis; however, the hazards will be similar to the other three systems but smaller in magnitude. This process was patterned after the PHA methodology performed on the U.S. Department of Energy (DOE) nonreactor nuclear facilities using DOE standards 1027 [1] and 3009 [2] and draws on U.S. Nuclear Regulatory Commission (NRC) regulations for radioactive byproduct materials detailed in the U.S. Code of Federal Regulations (CFR) 10 CFR 30 [3] and International Atomic Energy Agency Safety Guide NS- D-11 [4]. The PHA was performed using the following steps.

1. *Hazard Identification and Screening*

Hazards associated with the TCWS were identified including radiological/chemical/electromagnetic hazards and physical hazards (e.g., high voltage, high pressure, high temperature, falling objects). Hazards commonly found in industry were screened out during this process; the remaining hazards were termed "identified hazard."

2. *Hazard Categorization*

Identified hazards were categorized as to their potential for harm to the workers, the public, and/or the environment.

3. *Hazard Evaluation*

The design of the TCWS was examined to identify those initiating events that could expose the public, environment, or workers to the hazard should they occur. In addition the system was examined to identify mitigating features such as barriers that prevent exposure, although no credit is given for these features at this stage of the PHA. Finally, consequences to the public or workers were qualitatively assessed, should the initiating event occur and one or more of the barriers fail. Frequency of occurrence of the initiating event and subsequent barrier failure were qualitatively estimated.

4. *Accident Analyses*

Initiating events will be indentified and accidental sequences categorized so that accident analyses (e.g., failure modes and effects analyses [FMEAs]) are performed during the preliminary design of the TCWS when detailed information is available such as piping layout, size of equipment, location/types of controls and monitors, etc. Particular attention will be paid to those hazards that ranked high in both likelihood of release and magnitude of the resulting consequences given a release. As part of this more detailed analysis, the consequences will be assessed based on the mitigating features in place, and then the need for additional barriers and other measures to further reduce either the likelihood of release or the severity of consequences given a release will be identified.

2. Hazard identification/screening/categorization

All four PHTS have similar types of hazards. These include the following.

- High pressure
- High temperature

- Chemical [W and Be powder (only under accident conditions)]
- Electromagnetic field environments
- Cryogenic temperature environments
- Vacuum environments
- High voltage
- Kinetic energy
- Radiation

All hazards with the exception of radiation were screened from further review because they were common industrial hazards or they were not directly related to the TCWS. However, some hazards present in other tokamak systems may affect the consequences of an event initiating in the PHTS should a failure of that system occur (e.g., Be or W powder). This impact will be discussed later in the paper.

Tables 1–3 list the radiation hazards and their concentrations for each of the three systems reviewed. The hazards listed are present during many of the operational modes of the system (operation, standby, draining/drying, gas or water baking, and shutdown) However, they are bounded by the operational mode. These tables also show the categorization of the hazards.

The total curie activity in the three systems is below the NRC regulatory limit shown in column 4 of the tables. This limit represents the magnitude of the source term that if totally released without mitigation and under worst meteorological conditions would result in a dose of 10 mSv (1 rem) at 100 m from the release point. The French Regulatory Authority uses the same limit for off- site consequences. Thus, each individual PHTS loop would be considered as a low hazard system. Consequences resulting from failure of these systems would be limited to exposure to on-site personnel and would not be expected to impact the general public. The total activity level for the three FW/BLK loops is near the limit for unmitigated source term release should some common cause event result in the failure of all three loops. However, mitigation will be provided by the tokamak building such that the off-site consequences should still remain below the limit of 10 mSv at 100m.

In addition to the isotopes listed in Tables 1–3, the DIV/LIM and FW/BLK contain large activity concentrations (>10^6 GBq/m^3) of ^{16}N and smaller concentration of ^{17}N. These are quantitatively above the screening limit; however, they are screened out because their half-lives (7.4 sec and 4.17 sec) are so short that these radionuclides will rapidly decay following the plasma pulse. During operations no one is allowed inside the building; therefore, even though this radiation hazard is present during operations, there is no receptor present until after it has decayed (e.g., 1 minute of elapsed time from shutdown of the plasma pulse represents nearly 10 half-lives for ^{16}N and more than 12 half-lives for ^{17}N).

By way of comparison, the French Order (ESPN) issued in December 2005 concerning nuclear pressure equipment has established limits for total nuclear activity contained in a nuclear pressure system. For pressure equipment containing less than 370 MBq (<0.01 Ci) of activity, the system would be exempt from the order. For systems with activity levels in the range of 370 MBq–370 GBq (0.01 Ci–10 Ci), the system would be designated as N3 or a low hazard nuclear pressure system and require regulation. For systems with activity levels greater than 370 GBq (10 Ci), the system would be designated as N2 or a medium hazard, with a higher level of regulatory attention required. A high hazard system designation, N1, is reserved for pressurized water reactors. For compliance with this order, the tritium and ^{16}N activity levels are allowed to be reduced by a factor of 1,000.

3. Hazard evaluation

Several initiating events that could lead to the release of the radiation hazards were identified along with an estimated frequency range. These were divided into two categories, small breaks (<190 l/min) and large breaks (>190 l/min up to double ended guillotine pipe breaks). The initiating event frequencies were grouped into three designations shown in Table 4. They apply to the entire TCWS.

TCWS subsystems are similar in design and thus the set of initiating events will be the same for each system. Table 5 lists the initiating events for small pipe breaks along with their estimated frequency range [6].

The initiating events for large breaks (>190 l/min) are listed in Table 6. Several of the initiating events for large pipe breaks are similar to the small break events, but their frequency range is generally lower based on historical data.

Based on the maximum estimated activity level in any part of the TCWS, even the releases from large breaks will not exceed site boundary limits of 10 mSv at 100 m from the point of release. Thus the exposure risk will be limited to on-site personnel. If there is a large pipe rupture event in the DIV/LIM or FW/BLK piping, there is a possibility that the in-vessel activated dust and tritium inventories may be mobilized and released through the break due to a subsequent pipe failure inside the vacuum vessel after plasma disruption caused by the Fusion Power Termination System (this is a safety system that is activated automatically after detection of the primary ex-vessel break). These inventories would then be released into the tokamak building, but doses at the site boundary are still estimated to remain below the site boundary limits mentioned above [7].

If the largest divertor pipe is ruptured during baking operations (water temperature of 240°C), the resulting pressures in the building may exceed the building design pressure and pressure relief of the building may be required. It should be noted that during baking operations there is no plasma inside the tokamak; therefore, no in-vessel failure leading to bypass is postulated in this situation. When maximum concentration of radioactive contaminants is assumed, the expected site boundary dose because of short duration bursts to the atmosphere are minor compared to the General Safety Objectives of the Facility [7].

A small break in any of the piping would likely result in a localized release of a small portion of the total radioactive materials contained in the ruptured system. For large breaks larger quantities of radioactive material will be released involving larger areas of the tokamak building. Failure of the water/gas isolation valves could result in contamination of the gas baking/drying systems in other portions of the facility that may not usually be radiation control areas.

The TCWS design has incorporated a number of measures to either reduce the frequency of these initiating events or mitigate the consequences. These include reduction of the likelihood of an initiating event by proper design, maintenance, and inspection and mitigation of consequences by proper monitoring, controls, training, and procedures. Several of the important mitigation measures are listed below [7].

- Design of piping to American Society of Mechanical Engineers Process Piping Code, ASME B31.3
- Quality assurance and inspections per code
- Proper specification of components and materials for intended use and operational conditions
- Proper welding specifications, welder training, and procedures
- Pipe interaction prevention
- Water chemistry controls, cleanup, and filtering
- Maintenance and periodic inspection
- Intermediate loops on heat exchanger (accommodate heat exchanger tube failures)\
- Pressure relief into pressure suppression tanks
- Seismic isolation
- Piping stress and thermal analysis
- Floor drains and collection in drain tanks
- Dikes around tanks
- Plasma termination signals upon loss of cooling capability
- Double isolation valves and incorporation of monitoring of spaces between isolation valves
- Radiation monitoring
- Radiation protection program
- Work control programs

In addition to the containment of radioactive materials in the TCWS, the VV system is designed to be able to remove the residual heat resulting from the activation of materials from the components inside the cryostat after the plasma has been shutdown [8]. This system is to operate even under loss-of-off-site-power conditions. This function is performed under two modes of operation, forced convection if off-site power is available and natural convection if off-site power fails. To ensure redundancy, the VV heat transport system has two independent loops each capable of removing the residual heat load. There is no component redundancy in either loop. Because of the system redundancy, random failures leading to a loss of coolant in both loops are low frequency events. However, there are several common cause events that could result in a loss of coolant in both VV loops at a medium frequency level.

Potential common cause events that could cause loss of coolant in both VV loops are (1) loss of the six water-to-air heat exchangers located on the roof of the building due to wind or wind driven missiles, (2) severe pipe interactions caused by a large rupture in adjacent cooling pipes located in a common pipe chase, and (3) severe pipe interactions from some other energetic events. Loss of cooling to the VV may cause overheating which may exceed the temperature limits on the FW/BLK and DIV/LIM systems. To reduce this vulnerability to common cause events, a design change request has been introduced that will remove the need for active cooling of the VV as the principal means of removing residual heat from the system. Residual heat removal will instead rely on the heat capacity of the VV structure with subsequent long-term heat removal via heat transfer to the cryostat.

4. Conclusions

A hazard assessment of the TCWS has been performed. Radiation hazards were identified as the most serious hazard associated with TCWS. Several initiating events and their frequency ranges were identified that could result in the release of radiation into the tokamak building with possible exposure of on-site personnel. It was determined that the quantities of materials released from the failure of a single loop would not result in exposure risk to the general public. Proper design, maintenance, and operation of the TCWS will result in a significant reduction in the likelihood of the occurrence of these initiating events or a reduction in the consequences to on-site personnel should such an event occur.

The current design of the VV relies on active cooling to remove residual heat after the plasma is shut down. Vulnerabilities were identified in the current design that could prevent this functional requirement from being adequately achieved. Changes in the active cooling requirement are being considered for the project.

Acknowledgement

The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to

publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

References

[1] DOE, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports,* DOE-STD-1027-92, United States Department of Energy,1992 (1997).

[2] DOE, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses,* DOE–STD-3009-94, United States Department of Energy, 1994 (1996).

[3] U.S. Code of Federal Regulations, Title 10, Part 30, sections 70, 71, and 72. U.S. Government Printing Office, Washington, DC 20402. 2008.

[4] IAEA, *Protection Against Internal Hazards Other Than Fires and Explosions in the Design of Nuclear Power Plants: Safety Guide,* Safety Standards Series NS-G-1.11, International Atomic Energy Agency, 2004.

[5] V. Barabash, *Fluid Radioactivity Concentration for the ITER Tokamak Cooling Water System,* ITER D 26GLXV, 2008.

[6] L. C. Cadwallader, *Vacuum Systems and Primary Heat Transfer System Component Failure Rates and Repair Rates,* ITER/US/96/TE/SA- 05, March 28, 1996.

[7] L. Topilski, et al., *ITER Accident Analysis Report,* ITER D 2E2XAM v. 1.3, 2008.

[8] Systems Requirements Document (SRD) Tokamak Cooling Water System (TCWS) PBS 26-TC, 2009.

Abbreviations:

BLK	blanket
CFR	U.S. Code of Federal Regulations
DIV	divertor
DOE	U.S. Department of Energy
FMEA	failure modes and effects analysis
FW	first wall
LIM	limiter
NBI	neutral beam injector
NRC	U.S. Nuclear Regulatory Commission
PHA	preliminary hazards assessment
PHTS	primary heat transport systems
TCWS	tokamak cooling water system
VV	vacuum vessel

Table 1. Curie content of DIV/LIM system

Material	Activity concentration [5] (GBq/m^3)	Total curies (Ci)	NRC Curie limit (Ci)[3}	Hazard category
^3H	1850	7,250	20,000	low
^{14}C	0.2	0.78	50,000	low
Activated Corrosion Products	4.84	18	10,000	low

Table 2. Curie content of FW/BLK (note the total curie content in column 3 is distributed over three independent PHTS cooling loops)

Material	Activity concentration [5] (GBq/m^3)	Total curies (Ci)	NRC Curie limit (Ci) [3]	Hazard category
^3H	1850	19,300	20,000	low
^{14}C	0.2	2.3	50,000	low
Activated Corrosion Products	4.84	69	10,000	low

Table 3. Concentrations of radioactive materials in the vacuum vessel (note the total curie content in column 3 is distributed over two independent PHTS cooling loops)

Material	Activity concentration [5] (GBq/m^3)	Total curies (Ci)	NRC Curie limit (Ci) [3]	Hazard category
^3H	76	657	20,000	exempt
^{14}C	.0.00022	0.0019	50,000	exempt
Activated Corrosion Products	.06665	.57	10,000	low

Table 4. Initiating event frequency ranges

Designation	Frequency range	Context of frequency (ITER terminology)
H	$1–10^{-2}$/yr	Incident (expected in lifetime of plant)
M	$10^{-2}–10^{-4}$/yr	Accident condition
L	$10^{-4}–10^{-6}$/yr	Design basis event

Table 5. Small break initiating events and frequency ranges

Initiating event	Frequency range designation (table 4)
Weld failures	H
Pipe failure (erosion/corrosion)	H
Isolation valve leaks (liquid/liquid)	H
Pump seal and gasket leaks	H
Leaking or momentary opening of relief valves	H
Fitting and flange leaks	H
Liquid/gas isolation valve leaks	H
Human errors	H
Seismic events (less than design basis)	M
Falling objects	M
Heat exchanger tube leaks	M
Tank leaks	M
Water hammers	L
Fatigue failures	L
Thermal stress	L
Radiation damage	L
Energetic impacts (pipe whip, magnetic current loss, plasma termination, dust explosion, hydrogen explosion)	L

Table 6. Large break initiating events and frequency ranges

Initiating event	Frequency range designation (table 4)
Stuck open relief valves	M
Isolation valve failures	M
Pump/valve body failures	M
Human errors	M
Tank ruptures	L
Falling objects	L
Greater than design basis seismic events	L
Large water hammers	L
Fatigue failures	L
Thermal stress	L
Over pressurization (greater than design limits; no relief valve action)	L
Radiation damage	L
Large energetic impacts	L
Multiple heat exchanger tube ruptures	L