HIGHLIGHTS OF CANADIAN ACTIVITIES IN FUSION SAFETY

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ABSTRACT

A next-step experimental fusion reactor will likely have many of the features of a fusion power reactor except for tritium breeding and electrical power production systems. The proposed International Thermonuclear Experimental Reactor (ITER) will have a total (plasma plus direct heating) power output approaching 2000 MW (thermal). This level of performance (up from the 1 to 2 MW recently demonstrated at JET) requires significant quantities of tritium to be handled inside the facility. Hence, tritium safety is one of the key issues to be addressed in the design.

CFFTP is supporting the ITER conceptual design activity by design contributions, primarily to fuel cycle (tritium) related systems. As a result of the tritium safety R&D programs that have been in place for many years, in support of the CANDU program, Canada is a recognized world leader in tritium safety. While CFFTP has utilized fission relevant R&D to the greatest extent possible, some safety R&D programs have been established to address specific fusion safety concerns. In some instances, such programs have been co-sponsored by fusion groups outside Canada.

The paper describes the key safety issues associated with experimental fusion devices and how these issues are being addressed by the fusion community and by CFFTP.

1.0 INTRODUCTION

In the past few decades, the world fusion community has advanced from small plasma experimental devices to major experimental facilities such as JET (Joint European Torus), which recently demonstrated the capability for producing fusion power by sustaining up to 2 MW of plasma power for a few seconds, a major accomplishment in the world of fusion. Future tests in the JET facility anticipate even better power and energy performance.

Already, design work is underway on the next major fusion experimental facility - ITER (International Thermonuclear Experimental Reactor). ITER will be a truly international project, with major participation from Japan, Russia, the US and Europe. Canada's participation in ITER is through the European Community, with Canada contributing the equivalent of 10% of the European ITER budget, in technical and R&D services. ITER will be designed for a nominal fusion plasma power output of 1000 MW (thermal) sustained over 1000 to 2000 seconds. ITER will be a major project and will carry a price tag of several billion dollars, hence, the need for international cooperation.

Although an ITER-type machine is still some distance from a commercial fusion reactor, it will have the features of a commercial power reactor, with the exception of large-scale tritium breeding and electricity production. For this reason, many of the safety issues associated with ITER will be similar to those of future commercial machines based on the D-T fuel cycle. Tritium safety is almost synonymous with fusion safety. There are two characteristics of tritium that give rise to safety concerns: its radioactivity and its flammability and explosion potential. Coupled with the perceived need to make fusion much safer than fission, ITER participants have proposed safety targets that are exceedingly stringent and will ultimately lead to major constraints on the design of tritium systems.

2.0 FUSION SAFETY ISSUES

A brief overview of fusion safety issues is given below. As with fission reactors, there are both occupational and public safety concerns. Occupational safety considerations impact primarily on the extent of plant automation as well as remote maintenance capabilities. Public safety considerations deal primarily with containment of radioactive material and the health effects of potential radioactive releases.

2.1 Occupational Safety

2.1.1 Radiation Fields

Experimental fusion reactors such as ITER will produce high-energy neutrons (14 MeV), hence, shielding is a primary consideration for occupational safety. Furthermore, the materials of construction for ITER torus (mostly stainless steel) are exposed to neutron irradiation and themselves become radioactive. This means that once the reactor has become activated personnel access into the torus will not be possible and activities, such as replacing first wall components or maintaining diagnostic equipment inside the torus will have to be done by remotely operated robotic devices. Even so, radiation fields from activated equipment and structural components will be a major contributor to total dose. Based on ITER operating experience and the development of low activation materials, such as vanadium alloys and silicon carbide fiber composite ceramics, this dose component will be reduced in post-ITER machines.

2.1.2 Tritium Exposure

Occupational safety issues also arise from the tritium handling systems required to supply tritium fuel to the torus and clean up the tritium exhaust streams. The maintenance activity associated with tritium contaminated components such as valves and pumps, in tritium handling systems, is likely to be a significant portion of the overall occupational tritium dose. However, it is expected to be a small fraction of the total occupational dose, which includes neutron and gamma contributions. Canadian experience plus continued R&D work into more effective means of decontaminating components prior to maintenance should significantly reduce tritium occupational doses for both fusion and fission facilities.

2.1.3 Tokamak Dust

Experience from the JET facility and other devices indicates that a fine dust is produced from the torus walls during plasma operation. Depending on the first wall material, the dust can be activated or not, but regardless of the presence of activation products, the dust will contain tritium, as a gas, vapour or organic compound (eg., methane), and metallic hydrides. Suspension of the dust during a maintenance period requiring opening of the maintenance ports will require careful contamination control measures. At JET, such precautions have been taken to protect maintenance staff from tokamak dust. However, the concern to date has been primarily due the toxicity of beryllium, which is used as a first wall material, and not due to radiation. This will change once JET starts to operate with significant quantities of tritium and high neutron fluxes. The dosimetry and toxicity of tokamak dusk is currently receiving little attention.

2.1.4 Non-Radioactive Hazards

From an occupational safety viewpoint, fusion power reactors will have unique hazards relative to fission power reactors. They include: cryogenic fluids for pumping plasma impurities and for hydrogen isotope separation, large magnetic fields required for sustaining intense currents in the plasma and for controlling it, large radio-frequency and microwave fields for plasma heating, and large accelerators and pellet injectors for fuelling the torus with tritium and deuterium. Although the hazards associated with such devices are well recognized, the standards of protection for some of these have not reached the same level of maturity as radiation protection standards.

2.2 Public Safety

2.2.1 Accidental Tritium Releases

Because the reactor is heavily shielded to protect the magnets and operating personnel, public safety is not an issue during normal operation. Chronic tritium releases will be minute as a result of the proposed ITER emission targets. Public safety issues could arise from accident conditions that have the potential to release significant quantities of tritium and/or other radioactive material. In contrast with fission reactors, fusion reactors do not have a fuel overheating problem due to fission product decay heat generation after the reactor is shut down. The relatively small amount of decay heat from activation products does not pose a significant safety threat to the public. Although there are significant amounts of stored magnetic energy in a fusion reactor, there are means for dissipating it without posing a direct threat to the public. In short, in fusion reactors there is no equivalent of the fission core meltdown concern.

2.2.2 Accidental Tritium Releases from Shipping Containers

The fuel requirements for an experimental reactor such as ITER will amount to a few kilograms of tritium per year. As ITER is not expected to breed significant quantities of tritium, most of it will have to be shipped to the facility in a metallic hydride, i.e. a tritide, in stainless steel transportation containers. Once the tritium is absorbed on the metal getter, it must be heated to large temperatures for it to be released from the metallic solid. Even then, it will be largely contained by the stainless steel pressure vessel. Therefore, transportation accidents are not likely to give rise to the release of significant quantities of tritium.

In contrast, in the reactor facility itself, tritium will also be present in the gas phase. Hence, under accident conditions, it can potentially react with air in an explosive way providing a large driving force for releasing it to the environment. For this reason it is believed that the risk from transportation accidents is likely to be considerably smaller than that from reactor facility accidents.

2.2.3 Radioactive Waste Generation and Disposal

Of the tritium fuel injected into a tokamak reactor, only a small amount is burned (2 to 5%). The rest is recycled, hence, the fuel itself does not present a waste disposal problem. The product of the fusion reaction is non-radioactive helium, which does not pose any environmental or health problems.

The first-wall and divertor material, which is expected to be replaced several times during the life of an experimental reactor such as ITER, will require controlled storage and disposal, in the same manner as fission reactor waste. The extent of activation will depend on the neutron fluence and the choice of materials. Low activation materials such as beryllium and graphite do not require a long storage time prior to disposal in non-radioactive waste sites.

Structural materials such as stainless steel will become activated and will require long-term storage in radioactive waste disposal facilities. However, such structural materials, with the exception of those used in divertors, may not need to be replaced during the operational life of the reactor, although provision will be made for their replacement.

3.0 CANADA'S PARTICIPATION IN FUSION SAFETY

Canada's involvement in fusion safety work is focused on tritium safety, and more specifically on the safety aspects of tritium handling systems, where we have a recognized level of expertise. Our participation in fusion safety work is through attachment of safety analysts and engineers at international fusion facilities such as JET; through participation in international fusion projects such as ITER; and through the domestic tritium safety research program, which benefits both the fission and fusion communities.

3.1 Assistance to International Fusion Facilities

3.1.1 Staff Attachments

Safety analysts from Ontario Hydro, AECL, and the consulting community have been involved in the safety analysis of the JET facility for a period of six years, primarily through staff attachments. Together with experts from European countries, they have performed the necessary safety analysis and prepared the necessary licensing submissions to satisfy the regulatory requirements and to obtain the necessary permits for its operation. A significant amount of additional safety analysis is required to obtain permission to operate with substantial quantities of tritium in the near future. Canadian safety involvement at JET has focused on the safety design and safety analysis of the Active Gas (tritium) Handling System.

Staff attachments at operating facilities provide Canada an excellent opportunity to participate in fusion projects that are too costly for us to undertake independently.

3.1.2 Support Services

Safety analysis, such as dose calculations for tritium environmental releases, has been performed for both JET and TFTR (Tokamak Fusion Test Reactor) as support services from Canada, in addition to the staff attachments. Other safety services include Design Safety Reviews of tritium related systems.

3.2 Participation in the ITER Design Study

3.2.1 Fuel Cycle Systems Safety Analysis

CFFTP's contribution to the four partner ITER design study has been through the European ITER team. One of Canada's primary responsibilities on ITER is the design of fuel cycle systems. Accordingly, the key safety role at CFFTP is to support the design of such systems with the appropriate level of safety analysis. Some of this safety work is being performed in collaboration with ENEA - the lead agency in the Italian fusion program, which has the responsibility for fuel systems safety analysis on the NET (Next European Torus) reactor design.

Specifically, safety analysis efforts to date have focused on the isotope separation system and the fuel clean-up system. The objectives of the current preliminary safety analysis were:

a) to determine the conditions for which in-process detonation is possible,

b) to determine the design features required to eliminate oxygen from the process stream, and

c) to determine the maximum credible detonation resulting from a process failure giving rise to the release of hydrogen isotopes into the tritium building.

Safety assessments of these systems have included both event sequence analysis and consequence analysis. Preliminary analysis results of the current fuel clean-up system design indicate that only minor design changes would be required to meet current safety standards. Also, early indications from the isotope separation system analysis suggest that the maximum credible detonation would be the equivalent of a blast from about 1 kg of dynamite. This is an order of magnitude lower than what is predicted in a similar scenario for the Darlington Tritium Removal Facility.

3.2.2 Containment Design Assist Analysis

In addition to fuel cycle systems, containment design has been an area of interest to CFFTP. Contributions to the ITER study have been made in the form of containment safety design concepts submissions as well as design assist analysis. The objective of the design assist analysis[7] was to determine peak pressures in various containment zones, as well as the vent area required between zones to limit differential pressures to 15 kPa. For example, calculations performed for the largest pipe break in the ITER cooling system demonstrate that containment integrity (pressures below 30 kPa) can be maintained with only a vent area of 10 m^2 in the inter-zone boundary. This can be achieved without external venting or active pressure suppression systems. The calculations were performed with the PRESCON2 containment code.

A thermalhydraulic model of the largest ITER cooling circuit (shield cooling) was developed to determine the mass and energy discharge rates into containment. The CATHENA computer code was used for this.

In addition to external pipe breaks, some analyses were performed for in-vessel cooling tube breaks. These showed that vessel integrity would be maintained by providing a vent area of less than 1.0 m^2. For even the largest in-vessel pipe break, a total vent area of 10 m^2 would ensure vessel integrity. Even this area is a modest requirement considering that it only represents a rupture disc of less than 1 m diameter on each of 16 torus exhaust ducts. Each duct is about 2 m in diameter.

3.3 Tritium Safety Program

3.3.1 Dosimetry

Research continues into the potential health effects of tritium and particularly the means of quantifying the biologically significant dose that can result from exposure to HT, HTO, and tritiated hydrocarbons. Past efforts have concentrated on understanding the effects of tritium associated with inhalation and ingestion. Current efforts are focused on a third exposure pathway: skin exposure from contact with HT contaminated surfaces[1]. Metallic surfaces used in tritium systems (eg., piping, valves, pumps) may be also contaminated with very thin oil films, which react with tritium to form tritiated hydrocarbons. Hence, the level of hazard depends not only on the amount of tritium contamination, but also on the form in which it exists.

Skin contact experiments performed with rodents indicates that the percentage of activity transferred from the metal surface to the skin increases linearly for up to 15 to 30 seconds and then becomes constant. The data also suggest that the skin dose, rather than the whole body dose resulting from the skin up-take, may be the limiting one.

3.3.2 Environmental Tritium Modelling

In contrast with CANDU fission plants, the tritium in fusion facilities exists primarily in gas form (T_2 or HT), as opposed to tritiated vapour or liquid. Hence, tritium releases from fusion facilities are expected to be primarily in the form of HT gas. However, tritium gas will react with soil bacteria and with vegetation in the environment, converting to the vapour form (HTO). CFFTP has funded the development of environmental models for assessing the impact of tritium releases on the environment and the public. This has included laboratory research and field test work, to establish the tritium transport and conversion rates in the environment, and to verify the computer models. This pioneering work has led to international validation experiments in the natural environment.

A significant result of this world-leading effort was a reduction in the amount of conservatism that had been previously built into dose estimates for elemental tritium releases. This was a key factor in establishing the regulatory emission limits for tritium at the Darlington TRF.

The most recent version of the ETMOD[8] (Environmental Tritium Modelling) code was demonstrated, during benchmark comparisons that were part of the International Thermonuclear Experimental Reactor (ITER) design studies, to be the best available code for predicting tritium environmental effects. This code is now fully documented and available for use by the international fusion community.

3.3.3 Monitors and Samplers

Tritium monitors are a key part of the process for controlling and maintaining occupational and public doses as low as reasonably achievable. Close interaction between laboratory and industry in Canada has helped in the development, testing and production of tritium measurement devices for personnel and effluent monitoring. CFFTP and AECL Research co-funded the development of the Scintrex Portable Tritium Monitor, which is in wide use both in CANDU power stations, and in international tritium laboratories.

AECL Research has conducted a program of comparative field testing of passive diffusion samplers against conventional active samplers. These passive samplers can be employed in chronic monitoring of the workplace, environmental compliance monitoring, and in environmental research programs required for model verification. Some passive samplers can also discriminate between HT and HTO[2,3].

3.3.4 Component Decontamination

Significant occupational doses can arise from maintenance operations on tritium contaminated components, but this can be substantially reduced by component decontamination, prior to maintenance work. Improved methods that minimize waste generation and decontamination risks are being developed at the Ontario Hydro Research Division, where glow discharges in a variety of gases have recently been studied. Stainless steel vacuum fittings with surface activities ranging from 30-800 kBq/m2 have been exposed to glow discharges in three gases: hydrogen, helium, and argon. Following several brief exposures, the surface contamination has often been reduced below 300 Bq/m2 - the minimum detectable level in these experiments. Argon plasmas have been shown to be particularly effective for tritium decontamination[4].

3.3.5 Storage Beds

Uranium beds are commonly used for tritium storage in experimental handling facilities and at both JET and TFTR. The known propensity of uranium for pyrophoric combustion has raised safety questions in the event of accidental ingress of air to a large bed containing tritium. An experimental program was carried out at the Ontario Hydro Research Division with the support of CFFTP, the Princeton Plasma Physics Laboratory, and the Idaho National Engineering Laboratory[5]. Uranium beds of 5 to 3000 g were tested with exposures to air, nitrogen, and oxygen. In every test, the oxidation reaction was limited and produced only a modest temperature rise. No measurable tritium releases from the bed were observed. It was concluded from this work that the hazard associated with an air-ingress accident involving a uranium bed is minimal, and should not be of concern.

3.3.6 Air Detritiation Systems

Drier technology developed for CANDU plants to recover heavy water escaping into equipment rooms is being adopted in fusion facilities for removing airborne tritium in operating areas of the plant, and for emergency clean-up.

A fully integrated confinement and air detritiation system (ADS) is being designed for the ITER fusion reactor concept. This system will include normal ventilation with box-up capability and pressure control to maintain radioactive zoning under normal operating conditions. In the event of a tritium release (either HT or HTO), the system will isolate the release, maintain the affected area sub-atmospheric with respect to its surrounding areas, and perform the actual detritiation of the affected area. This limits the impact of the spill, and minimizes occupational radiation doses, and emissions to the environment.

An R & D program has been initiated in support of the above work.

3.3.7 Sorption/Desorption

The sorption/desorption characteristics of different architectural surfaces and coatings for elemental tritium have been studied in the laboratory. The objective is to determine the most appropriate materials and surface coatings for equipment and architectural surfaces for minimizing tritium up-take. Using small specimens, AECL Research has been conducting systematic, "bench-scale" studies of the sorption/desorption behaviour of HT and HTO on a variety of materials and coatings[6]. The results of this work indicate that the desorption rate for HT is much greater than that for HTO. Another key conclusion of the work is that surface finish is just as important as the type of material in determining the sorption/desorption behaviour of HT and HTO.

The results of this work assist in determining the size of air detritiation systems and the rate of attenuation in tritium airborne concentrations following accidental releases.

4.0 CONCLUSIONS

Although Canada's role in international fusion projects such as JET and ITER is modest in dollar value, it is significant in technical value. Experience gained from the operation of CANDU generating stations, the Darlington Tritium Removal Facility and domestic tritium R&D has given Canada unique skills and experience and opportunity to participate in world class fusion projects. CFFTP intends to maintain its presence in international fusion projects and to support tritium safety R&D that is of benefit to both the fission and fusion industries. Such participation will equip Canada to share in the long-term benefits promised by fusion energy.

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