TRITIUM IN FUSION REACTOR COMPONENTS*

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ABSTRACT

When tritium is used in a fusion energy experiment or reactor, several implications affect and usually restrict the design and operation of the system and involve questions of containment, inventory, and radiation damage. Containment is expected to be particularly important both for high-temperature components and for those components that are prone to require frequent maintenance. Inventory is currently of major significance in cases where safety and environmental considerations limit the experiments to very low levels of tritium. Fewer inventory restrictions are expected as fusion experiments are placed in more-remote locations and as the fusion community gains experience with the use of tritium. However, the advent of power-producing experiments with high-duty cycle will again lead to serious difficulties based principally on tritium availability; cyclic operations with significant regeneration times are the principal problems.

INTRODUCTION

As fusion energy development approaches the time when ignited plasma burns and realistic technology and engineering experiments are needed, it will be necessary to handle significant quantities of tritium in these experiments; when fusion power reactors are developed, the quantities of tritium involved will be very large by present standards. The use of tritium in these experiments and reactors will have a major impact on the design and operation of the facilities. The issues to be addressed during consideration of tritium use in fusion facilities can be divided into three groups: (1) containment or release of tritium, (2) tritium inventory, and (3) materials problems. The relative importance of items in each set of considerations depends on the particular component or reactor design being considered.

Containment or release of tritium will not always include the most difficult design problems. However, before fusion energy can establish and

maintain a reputation as a clean and safe energy source, environmental and safety issues must be given a high priority during the development as well as the design/construction/operation stages of the program. Although it is convenient to divide the containment issue into two parts, steady or regular releases and accidental releases, the two are not necessarily independent questions.

Inventory issues are most critical for the first fusion reactors constructed, because the availability of tritium may be limited by existing production facilities, and the cost of initial tritium inventories produced from fission reactors will be high. The Department of Energy currently charges \$0.75/Ci for tritium sold in larger quantities. However, as fusion reactors begin to produce tritium, the cost of tritium must decline considerably; otherwise fusion energy will not be economically viable. Later reactors may have tritium available from previous fusion reactors at low and reasonable costs, but special care will still be needed to keep the inventory low enough so that the tritium doubling time in the reactors matches the doubling time needed for introduction of fusion into the energy economy. The doubling time is proportional to the ratio of the reactor inventory and the breeding ratio; thus inventory can be as important as breeding ratio once a ratio greater than unity is achieved.

Safety is an important factor in the inventory issue, especially the maximum release in the event of an accident. Obviously, the more tritium present in a facility, the larger the potential consequence of a major accident, but one should not take a simplistic view when assessing the accident hazard and simply equate the risk to the total inventory. The form and location of the tritium in various portions of the inventory should also be considered. Careful design can segment the major inventories and disperse critical items so that the likelihood for escape of a major portion of the inventory during a single accident or chain of accidents is minimal. Multiple containment with trapping or recovery equipment can reduce the risk even more.

Material selection throughout a fusion facility must include consideration of compatibility with tritium, which is often not unique to fusion energy; much can be learned from data and experience gained in other earlier programs that

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involved significant quantities of tritium.¹ Material problems may be divided into two groups of effects, radiation and hydriding (including helium deposition). Radiation effects are most severe for organic materials such as plastics and elastomers, which are frequently used for gaskets and seals. Lubricating and pump oils can also absorb tritium and be damaged by the beta-decay radiation; perhaps more importantly, the absorption of tritium makes the oils radioactive and thus a significant hazard to personnel. The effects of tritium on plastics and elastomers varies from material to material,^{1,2} but special care should usually be taken to avoid exposing halogen-containing materials such as vinyls or fluorocarbons to significant tritium concentration. Not only are these materials degraded, but the degradation products are corrosive.^{2,3}

Although metal properties can be degraded by absorption of tritium or any hydrogen isotope, many materials can be used with even high-pressure hydrogen, and much literature and experience is available to guide the designer in material selection. The unique feature of tritium is its radioactive decay to He³. This is a problem only for tritium absorbed within the metal. Both the radiation energy deposition and the helium residue can degrade the metal. Helium tends to accumulate at grain boundaries and contribute to embrittlement.⁴

TRITIUM RELEASE MECHANISMS

Tritium can escape from fusion systems through the usual small leaks around welds and fittings, through normal repair or replacement of components, through accidental failures, and by permeation. The last path is almost unique to hydrogen isotopes and has thus received considerable attention in fusion reactor studies. Most normal releases from process equipment can be prevented from escaping to the environment by enclosing the critical equipment items in secondary enclosures that are capable of removing tritium from the enclosure atmosphere, which avoids accumulation and eventual escape of tritium from the enclosure. However, one release path that cannot be contained within a secondary enclosure involves permeation of tritium from the blanket breeding material into the coolant and then into the steam generator. Once tritium reaches the steam system it is usually assumed to be released to the environment. The steam system can provide useful surge capacity to limit the effects of a sudden large accidental release of tritium by this path, but the need for "blow down" capabilities to handle sudden changes in power demand and normal leakage from turbogeneration equipment prevents effective containment of a steady loss of tritium to the steam system.

Permeation losses of most concern occur with high-temperature reactor designs, that is, those designs with blanket temperatures of 700 to 1000°C. Studies of early designs of high-temperature systems with high thermal efficiencies indicated that permeation losses, especially via the coolant/steam

generator, would determine the maximum allowable tritium concentration or pressure in the blanket.⁵ The high-permeation rates result from higher pressures of tritium in the blanket (for the same concentration), from higher permeability of metals at high temperatures, and from the selection of high-temperature structural materials that were also highly permeable to hydrogen (niobium⁶ or vanadium). Recent designs of near-term devices using stainless steel structure and temperatures below 500°C give permeation rates that are too low to be significant as shown in the comparison in Table 1.^{3,7} Since these are the fusion designs of most-current interest, permeation now seems less important than it did a few years ago.

Once the permeation rate is reduced, the principal paths for tritium escape become more conventional. These include leaks through seals, through imperfect welds, and during routine maintenance and replacement of components. Although the seriousness of tritium containment should not be underestimated and special care must be taken to reduce leaks, it is reassuring that the problems and approaches are not generically different from those used in handling any highly hazardous or toxic gas. Furthermore, secondary containment with tritium trapping from the secondary atmosphere can further reduce tritium escape to the environment and provide especially important protection in the event of sudden, large accidental escape of tritium.

INVENTORY CONSIDERATIONS

The principal areas where large inventories of tritium are likely to occur in a fusion reactor system are (1) in the cryogenic distillation equipment; (2) in all cyclic operations such as cryogenic vacuum pumps, getter pumps, and collectors; (3) in the blanket and blanket processing system; and (4) with fuel storage and surge capacity. An effort will be needed throughout the fusion system to minimize inventory, but special care will be required with the cyclic operations and with the blanket.

Cyclic operations that handle the entire throughput of fuel must function with short cyclic periods, especially when the fraction burn is low and thus the fuel throughput per unit power is high. The throughput for a 1000 MW(e) system can contain a few kilograms of tritium per day. Cycle times of no more than 4 to 8 hr are likely to be acceptable. The time required to regenerate the cyclic devices is critical. Cryopumps can be regenerated very quickly except when water must be removed from molecular-sieve sorption pumps. Normal regeneration of condensation or cryosorption pumps to recover deuterium-tritium (D-T) or helium should take no more than a few minutes and add little to cycle times and inventories. However, slow accumulation of higher-molecular-weight tritium-bearing compounds (such as water) on cryosorption pumps will require a periodic slow regeneration at high temperatures (~200°C).

Table 1. Comparison of tritium permeation rates for stainless steel and niobium

Structural material	Lithium temperature (°C)	Tritium concentration (wppm)	Permeation rate ^a (Ci/day)
316 Stainless Steel ^b	500	1	10 ⁻³
	500	10	10 ⁻²
Niobium ^c	800	1	2 x 10 ⁶
	800	10	2 x 10 ⁵
	500	1	2 x 10 ⁵
	500	10	2 x 10 ⁴

^aLithium exposed to about 12,300 m² of surface area, 5 mm thick.

^bSee reference 7.

^cSee reference 6.

However, getter materials such as zirconium-aluminum and titanium, which have been proposed for use as pumping devices, present more serious regeneration problems. The regeneration can be slow and require several hours at very high temperatures and high vacuum. The regeneration time and the number of cycles for which they can be used are likely to be the critical issues in their selection or rejection for fusion applications. The difficulties of quantitative recovery of tritium from some materials such as titanium for even long regeneration times may eliminate their use.

Other than breeding capabilities, inventory considerations are the principal tritium issues in the selection and design of blanket systems. (Radiation damage and heat removal are, of course, other serious issues.) The equilibrium retention of tritium and the rate of release must also be considered. Because lithium metal has a high affinity for tritium, the tritium pressure at the maximum allowable inventory (concentration) is very low and offers little driving force for removing the tritium, which is why lithium processing is difficult. No technique has been developed for recovering tritium from lithium at the concentrations acceptable in fusion reactors (<1 ppm), but sorption by yttrium^{8,9} and extraction by molten salts¹⁰ appear to be promising.

There is increasing interest in the use of solid lithium compounds rather than liquid lithium metal as the breeding media in fusion reactors, principally because lithium metal is combustible and would release tritium in the event of a fire. This increased interest in solid lithium compounds

is illustrated in the current "STARFIRE" design¹¹ in progress at ANL. Most lithium compounds offer breeding ratios that are marginal or clearly less than unity, but the effective use of neutron multipliers may make some of these compounds acceptable. Lithium oxide is, however, an exception because it is clearly capable of good breeding ratios. Although most lithium compounds that have been considered for fusion blankets have little affinity for tritium, the principal question affecting tritium inventory is the "rate" at which tritium is released from these materials. The average residence (retention) time of tritium atoms in the blanket should be no more than a few days. Since most recent designs call for relatively cool blankets (<500°C), tritium release rates are not necessarily as rapid as needed. Lithium oxide is a possible exception because it may retain significant quantities of tritium for considerable times. Alkali metal hydroxides are not easily decomposed, especially at the temperatures proposed for fusion blankets; thus the ability of lithium oxide to release all of its tritium rapidly (low inventory) has been questioned.

Another potential source of significant tritium inventory is in the structural material of those reactor designs such as NUMAK, which use zirconium or titanium structure, but this is not likely to be important for stainless steel systems.

CONCLUSIONS

In developing conceptual designs and evaluations of fusion reactor systems, all of the tritium issues for all components must be considered.

It is not sufficient to consider a material or a technique that satisfies only a single criterion; each operation must use materials and techniques that meet all requirements. Some of the more frequently ignored requirements are regeneration rates for cyclic operations and process (or release) rates for blanket materials.

11. STARFIRE: A Commercial Tokamak Reactor, ANL/FPP/TM-125 (1979).

REFERENCES

1. T. B. Rhinehammer and P. H. Lamberger (ed.), *Tritium Control Technology*, WASH-1269 (1973).
2. J. L. Scott (ed.), *The Fusion Reactor Materials Program Plan: Section IV. Special Purpose Materials*, USDOE/ET-0032/4 (1978).
3. *U.S. INTOR*, the U.S. Contribution to the International Tokamak Reactor Workshop, November 1979.
4. D. G. Atteridge et al., "Effects of Helium Implanted by Tritium Decay on the High Temperature Mechanical Properties of Niobium," pp. 307-30 in *Radiation Effects and Tritium Technology for Fusion Reactors*, ed. by J. S. Watson and F. W. Wiffen, CONF-750989, Vol. 2 (March 1976).
5. J. S. Watson et al., "Evaluation of Several Liquid and Solid Tritium Breeding Blankets," pp. 289-315 in *Radiation Effects and Tritium Technology for Fusion Reactors*, ed. by J. S. Watson and F. W. Wiffen, CONF-750989, Vol. 3 (March 1976).
6. R. W. Webb, *Permeation of Hydrogen Through Metals*, Atomics International Report NAA-SR-10462 (July 1965).
7. J. T. Bell and J. D. Redman, "Tritium Permeation Through Steam Generator Materials," pp. 1577-82 in *Proceedings of the 14th Intersociety Energy Conversion Engineering Conference*, Vol. 2, Boston, August 1979.
8. J. B. Talbot and S. D. Clinton, "Liquid Lithium Blanket Processing Studies," *Proceedings of the 8th Symposium on Engineering Problems of Fusion Research*, San Francisco, November 1979 (to be published).
9. S. D. Clinton and J. S. Watson, "The Solubility of Tritium in Yttrium at Temperatures from 250 to 400°C," *J. Less-Common Met.* 66: 51-57 (1979).
10. J. R. Weston et al., "Chemical Processing of Liquid Lithium Fusion Reactor Blankets," pp. 1572-76 in *Proceedings of the 14th Intersociety Energy Conversion Engineering Conference*, Vol. 2, Boston, August 1979.