SAFETY ISSUES ASSOCIATED WITH MOBILIZED ACTIVATION PRODUCTS IN SELECTED APEX DESIGNS

K. A. McCarthy, D. A. Petti, R. L. Moore, and B. J. Merrill
Fusion Safety Program
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, Idaho, USA 83415-3860
e-mail: km3@inel.gov

ABSTRACT

In the APEX (Advanced Power Extraction) project, safety and environmental concerns are considered up front as designs evolve so that the goal of safety and environmental attractiveness is realized. Because the neutron and surface heat loads are higher in APEX designs than those in conventional fusion designs, decay heat and activation are generally higher presenting an increased challenge when justifying the safety case. Potential first wall materials that can function adequately under higher neutron and heat loads include materials such as tungsten and molybdenum. The activation products of both these materials are radiologically hazardous and mobilizable under accident conditions. We have examined a number of APEX concepts to determine the ability of the design to remove decay heat from the plasma-facing surface during a loss of coolant and air ingress event. In this paper we concentrate on mobilization of first wall materials during ingress events, and provide guidance to enhance the safety characteristics of APEX designs that utilize tungsten and similar high heat load materials.

INTRODUCTION

The ultimate goal of the APEX project is to develop designs that make future fusion energy systems more commercially competitive. These concepts must be able to efficiently extract heat from in-vessel systems with high neutron and surface heat loads while satisfying all fusion power technology requirements and maximizing reliability, maintainability, and safety and environmental attractiveness. Safety and environmental issues are being considered up front as designs evolve so that the goal of safety and environmental attractiveness is realized. Designing safety into the design concepts as was done in the ITER project [1] results in less complex systems than retrofitting the design to meet safety requirements.

Potential first wall materials that can function adequately under higher neutron and heat loads include materials such as tungsten and molybdenum. Both of these materials produce activation products that are radiologically hazardous and mobilizable under accident conditions [2-3]. In most APEX designs, the plasma facing surfaces of these materials are covered with a liquid to protect the structure and/or remove heat. In addition, SnLi, a "new" coolant material that is under consideration as a liquid surface [4], can pose a radiological hazard because of the tin component.

Screening Criteria

The designs under development in the APEX project are at a pre-conceptual stage, lacking the detail needed for a comprehensive safety analysis. However as part of the APEX project, we have developed a set of screening criteria that are used at early stages of design to identify potential safety issues that could be difficult to solve. The criteria cover four areas: 1) mobilizable in-vessel tritium inventories, 2) decay heat (leading to mobilization of activation products, 3) chemical reactivity/combustible gas generation, and 4) waste/environmental. In this paper, we focus on decay heat.

A design must adequately transfer heat from plasma-facing surfaces to ensure that mobilization of hazardous materials is minimized. Although the specific temperatures above which mobilization is a potential safety issue depend on the specific material, general guidelines for long-term (decay-heat driven) accident temperatures are:

- Peak long term temperature < 500°C, little activation product mobilization expected
- Peak long term temperature 500-800°C, activation product mobilization is a concern and this source must be considered; can probably accept some confinement degradation and still meet no-evacuation with proper design
- Peak long term temperature > 800°C, significant activation product mobilization expected; level of confinement needed may be high and may threaten ability to meet no-evacuation

While these guidelines are not strict rules, they provide some guidance early in the design process as to whether design changes will be needed to meet no-evacuation limits (less than 10mSv off-site dose in the U.S. as outlined by the DOE Fusion Safety Standard [5]).

In this paper we present results of Loss of Coolant Accident (LOCA) analyses that were done to estimate long-term temperatures and provide guidance to designers to help them make the designs better from a safety point of view (e.g., provide good heat transfer paths that will limit long-term LOCA temperatures and hence limit mobilization). The CHEMCON code [6] used in these calculations was developed to analyze decay heat driven thermal transients in fusion reactors.

<u>APEX Designs Analyzed</u>

We carried out LOCA calculations for four different APEX designs:

- He-cooled, refractory alloy first wall/blanket (slowly moving liquid lithium breeder with tungsten alloy structure) [7]
- APPLE Concept (SiC structure with flowing LiO_2 particulate breeder; total blanket thickness of ~40 cm)
- CLIFF Concept (V structure with liquid breeder) [8]
- Thick Liquid (Pocket) Concept (a thick, ~50 cm, layer of liquid breeder flows over the ferritic steel structure facing the plasma) [8]

The radial builds for all of the designs are not included in this paper due to space constraints, however the characteristics that are most significant to the analyses (i.e., materials and coolant thickness) described here are given above.

RADIOLOGICAL HAZARD OF MATERIALS

The radiological hazard of a material depends on the material, neutron wall loading, and fluence. Figure 1 shows the radiological hazard of representative APEX materials (molybdenum, silicon, vanadium, tin, and tungsten) in Sieverts per kg (expressed as specific early dose) of irradiated material. These values are based on activation calculations done by Culham Laboratory [9-10], with a neutron wall loading of 4.15 MW/m^2 and an irradiation time of 2.5 years. The doses are based on a ground-level release at 1 km downwind distance using stability class D, 4 m/s wind speed, and no rain. This fluence is lower than that in APEX designs, therefore the relative values of the specific early dose are more relevant than the absolute values. This metric is useful when evaluating the relative hazard of tokamak dust, for example; the dust composition is generally assumed to be the same as the material from which it was produced [11].

Oxidation, however, can preferentially mobilize some elements over others. An example of this is that tungsten (with elements such as rhenium and tantalum added to simulate transmutation products) exposed to air, results in mobilization of more rhenium (by mass) than tungsten [12] (see Figure 2), even though the composition of the material is primarily tungsten. Conversely, when exposed to steam, more tungsten than rhenium is mobilized [13] (see Figure 3). Additionally, oxidation-driven mobilization is a strong function of temperature, so the temperature profile throughout the accident must be known to assess the hazard due to this source term.

RESULTS OF LOCA CALCULATIONS

Initial calculations with the CHEMCON code assume complete loss of coolant. For the He-cooled design, the slowly moving liquid lithium breeder (He is the coolant in this design), is not breached. The CLIFF and Thick Liquid Pocket designs may use lithium as the coolant; in calculations for these designs, the temperature rise that would occur from any lithium fire is not considered. If lithium is chosen as the coolant, calculations would need to be done that include this temperature rise.

We give detailed information on the He-cooled, refractory alloy design because it presents the greatest safety challenge (tungsten is a high decay heat, radiologically hazardous material). The other designs have lower decay heat because of the material choice (e.g., SiC, V alloy, ferritic steel), and the liquid layer that protects the material behind it (the He-cooled design is the only design analyzed that has a solid surface first wall).

LOCA Calculations for He-Cooled Refractory Alloy Design

The radial build used in the decay heat calculations and subsequent LOCA calculations is shown in Figure 4. Figure 5 shows the decay heat assuming an all-tungsten structure, and the decay heat representative of a material such as vanadium (approximated by decreasing the tungsten decay heat by a factor of ten).

Calculations show that a LOCA, with no active safety-grade cooling systems (therefore no active cooling), results in temperatures well in excess of 900°C during the entire accident (see Figure 6). Figure 7 shows the first wall temperature assuming under the same conditions an all-vanadium structure. Although overall temperatures are lower, temperatures are in excess of 900°C during the entire accident. The initial temperature spike is due to the disruption assumed to occur because of the in-vessel LOCA.

These calculations indicate that a safety-grade cooling system may need to operate during the accident to ensure that long term decay heat driven accident temperatures are low enough to satisfy safety requirements. Two options were considered: the vacuum vessel cooling system, and the tritium extraction system (with a flow rate of 20 kg/s). It is desirable to take advantage of existing systems, rather than adding additional systems. (The liquid lithium breeder flows through the blanket at a rate of 20 kg/s; the lithium is removed outside of the blanket in the tritium extraction system.) Figure 8 shows the first wall temperatures for these scenarios. The tritium extraction system is the more efficient method for decay heat removal because it removes the heat closer to the source, and does not rely on radiative heat transfer across the gap between the plenum and vacuum vessel. With the tritium extraction system operating, long-term accident temperatures remain below 800°C.

The tritium extraction system may require a higher tritium concentration than is provided by this scenario to extract the tritium efficiently. It may be necessary to segment the coolant in the blanket region, and use the 20 kg/s flow rate for the lithium in the front of the blanket (where the tritium concentration is highest). Because the decay heat is higher in the front part of the blanket, this should adequately remove the decay heat, but further calculations are needed to confirm this.

LOCA Calculations for Other Designs

The same type of analysis was done for the three other designs. Table 2 shows the peak temperature, and period of time that temperatures exceeded 800°C during the accident. Because of the large amount of tungsten used in the He-cooled refractory alloy design, active cooling was necessary to keep accident temperatures to an acceptable level. Similarly, it is primarily the Tenelon in the shield that is contributing to the high decay heat in the CLIFF design. Active cooling of the vacuum vessel reduces peak temperatures to 875°C, however temperatures are above 800°C for 3.5 days. It may be necessary to either actively cool the shield, or use a material other than Tenelon (which is a high manganese steel; manganese has high decay heat). Although the peak temperature during the transient for the APPLE design is above 800°C, the duration is less than 2 hours, and the relatively low radiological hazard of SiC makes this acceptable. The temperature in the thick liquid wall design never exceeded 675°C.

SUMMARY AND FUTURE WORK

Although the neutron and surface heat loads are higher in APEX designs than those in conventional fusion designs, these preliminary LOCA calculations indicate that safety criteria (and more specifically, no-evacuation guidelines) can likely be met. For some designs, such as the He-Cooled Refractory Alloy design, this will likely require the use of a safety-grade system to remove decay heat during accidents. It may be necessary to avoid the use of Tenelon in the shield in designs such as CLIFF; in that case, active cooling may not be necessary. For others, such as the Thick Liquid concept, a safety-grade system is probably not necessary. It is desirable to make any such system passive to increase the reliability of the system.

These preliminary scoping calculations are by no means sufficient for determining whether these designs will meet safety guidelines. They are meant as a starting point, and are used to make recommendations to designers so that safety is “built into” designs as they mature. As more design detail becomes available, further safety analyses will be done to ensure that safety requirements are met.

Acknowledgements

The authors would like to thank Hesham Khater from the University of Wisconsin for decay heat calculations; Clement Wong from General Atomics; Neil Morley, Alice Ying, and Karani Gulec from UCLA, Dai-Kai Sze from ANL, for design information on the various APEX concepts; and the entire APEX team. This work was supported by the US Department of Energy, Office of Fusion Energy Sciences, under DOE Idaho Operations Contract DE-AC07-94ID13223.

Table 1. Peak Temperature and Time Above 800°C for the designs analyzed

Concept	**Peak Temperature (°C)**	**Time Above 800°C (hours)**
APPLE	1275	1.2
CLIFF	875[a]	84[a]
He-cooled	800[b]	< 1[b]
Thick liquid	675	0

[a]With active cooling of the vacuum vessel
[b]With active cooling of the blanket region

Figure 1 Radiological Hazard of Representative APEX Materials (Carbon does not contribute significantly to the dose from irradiated SiC)

Figure 2 Mobilization of tungsten alloy in air

Figure 3 Mobilization of tungsten alloy in steam

Figure 4 Radial Build Used in LOCA Calculations

Figure 5 Decay heat values in the outer radial build were normalized to approximate V structural material in place of W and provide a lower bound for decay heat values

Figure 6 FW temperature assuming no active cooling during LOCA, all tungsten structure.

Figure 7 FW temperature assuming no active cooling during LOCA, all vanadium structure.

Figure 8 FW temperature for two scenarios: vacuum vessel cooling operates during LOCA, and tritium extraction system operates during LOCA.

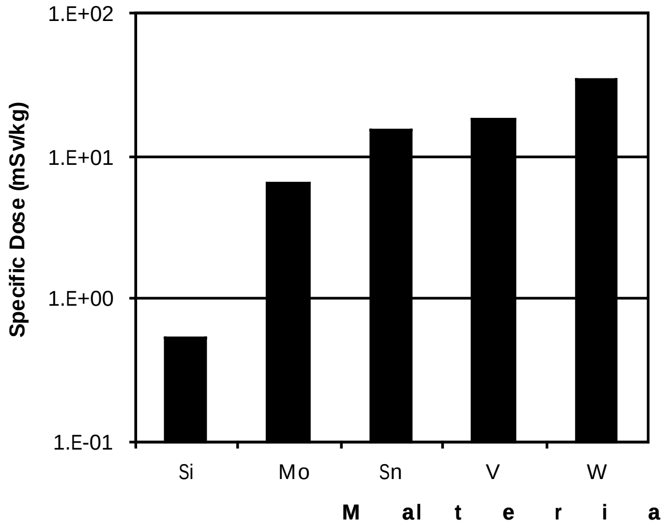


Figure 1

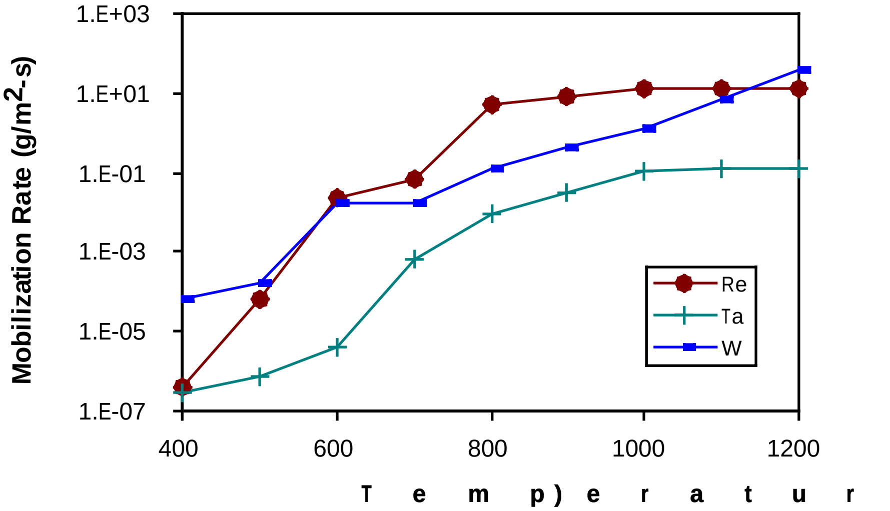
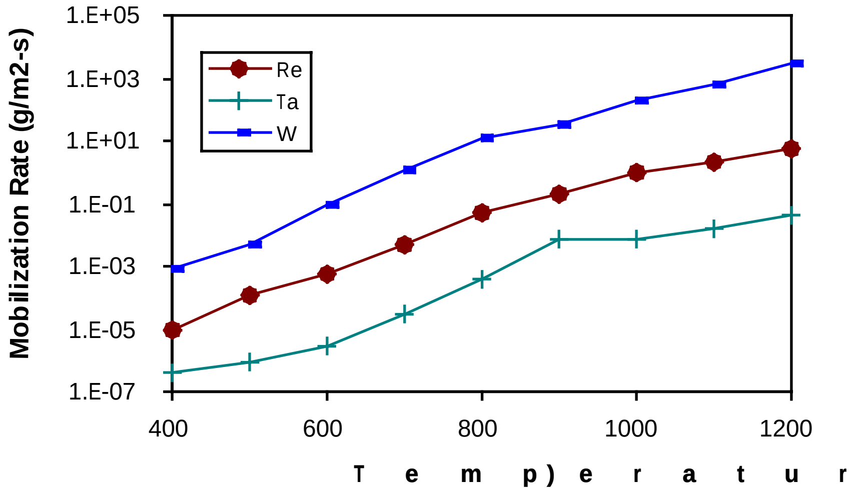


Figure 2.



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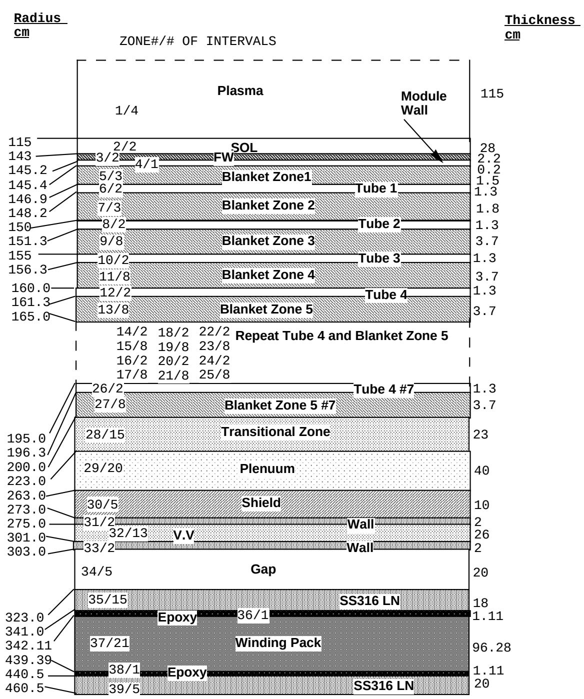

Figure 4

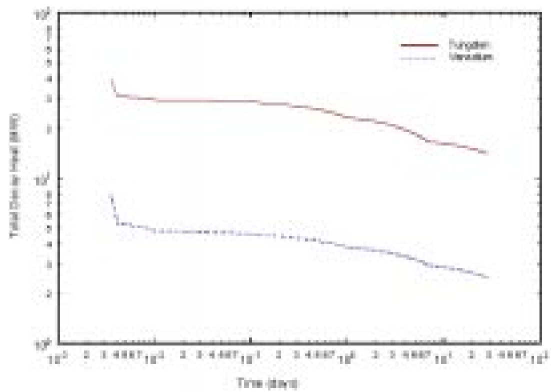

Figure 5

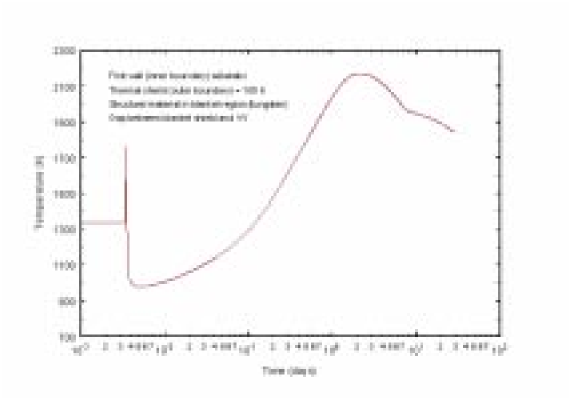

Figure 6

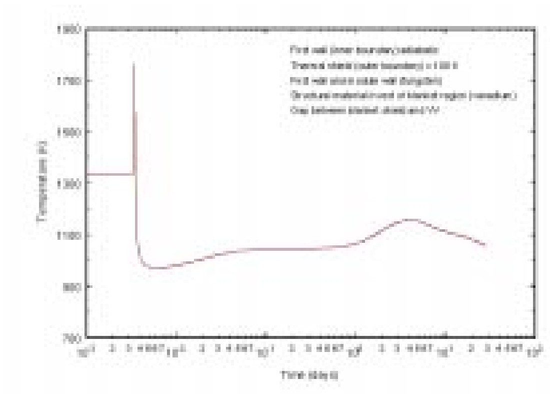

Figure 7

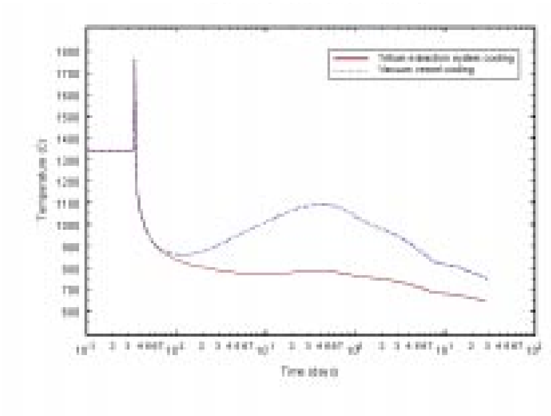

Figure 8

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