LOFA and LOCA in the TIBER-II Engineering Test Reactor

I.N. Sviatoslavsky, H.M. Attaya, M.L. Corradini, S. Lomperski

October 1987

UWFDM-739

. Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA.

LOFA and LOCA in the TIBER-II Engineering Test Reactor

I.N. Sviatoslavsky, H.M. Attaya, M.L. Corradini,
S. Lomperski

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

October 1987

UWFDM-739

. Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA.

LOFA AND LOCA IN THE TIBER-II ENGINEERING TEST REACTOR

I.N. Sviatoslavsky, H.M. Attaya, M.L. Corradini and S. Lomperski
Fusion Technology Institute
Department of Nuclear Engineering and Engineering Physics
University of Wisconsin-Madison
1500 Johnson Drive, Madison, WI 53706-1687

Summary

This paper describes the preliminary analysis of LOFA (loss of flow accident) and LOCA (loss of coolant accident) in the TIBER-II engineering test reactor breeding shield. TIBER-II is a compact reactor with a major radius of 3 m and thus requires a thin, high efficiency shield on the inboard side [1]. The use of tungsten in the inboard shield implies a rather high rate of afterheat upon plasma shutdown, which must be dissipated in a controlled manner to avoid the possibility of radioactivity release or threatening the investment. Because the shield is cooled with an aqueous solution, LOFA does not pose a problem as long as natural convection can be established. LOCA, however, has more serious consequences, particularly on the inboard side. Circulation of air by natural convection is proposed as a means for dissipating the inboard shield decay heat. The safety and environmental implications of such a scheme are evaluated. It is shown that the inboard shield temperature never exceeds 510°C following LOCA posing no hazard to reactor personnel and not threatening the investment.

Introduction

Recently, the focus of safety in nuclear power plants has been changing in response to public resistance to plant construction. In the fission industry the trend has been toward the so-called "inherently safe" reactors [2,3,4], which rely on natural properties of matter such as thermal conductivity and specific heat to achieve safety. An example of an inherently safe reactor is one in which the decay heat is absorbed by its components and is ultimately radiated to the surroundings without ever reaching dangerous levels of temperature. Although in fusion, designing for inherent safety must at all times be a goal, it is not always practical and for economic reasons, may not even be desirable. A second level of safety which may be appropriate for fusion is "passive safety." This scheme also relies on natural properties of matter but may also involve macroscopic motion of matter such as a gravity flow cooling loop actuated by a valve. Actuation, however, should be without active engineering systems or positive actions by reactor personnel.

In this paper we examine decay heat dissipation in the outboard and inboard breeding shields of TIBER-II, a compact tokamak engineering test reactor. The thickness allowed for the inboard shield necessitates the use of tungsten for protecting the magnets. Tungsten has a high decay heat and a low specific heat, making it impossible to be designed as inherently safe. We have therefore proposed a passively safe system for the inboard shield, utilizing natural circulation of air through the cooling channels with ultimate discharge through a 40 m stack. The outboard shield which consists of beryllium and steel has sufficient thermal capacity to qualify as inherently safe.

LOFA and LOCA Analysis

During normal reactor operation, a number of operational transients may occur when the reactor undergoes an unsteady-state event, such as a power-cooling mismatch. Such transients may be loss of flow (LOFA) or loss of coolant (LOCA), the latter being the more serious of the two. Analysis of this nature has the purpose of insuring that such transients will not pose undue hazards for reactor personnel and will not threaten the investment. An important goal of this design is that recovery from such an accident be accomplished by purely passive means, i.e. that it be done without active engineering systems or positive actions from reactor personnel. The analysis assumes that the plasma stays on for 10 seconds following the start of a transient. During this time the transient can be detected and the plasma quenched. Further, in the case of LOCA, the assumption is made that the coolant is lost instantaneously.

A LOFA transient occurs when a circulating pump fails for some reason and the coolant ceases to flow. Under normal conditions, a backup pump will automatically kick in and operation will proceed uninterrupted. In this design, the breeding shield is cooled with an aqueous solution of $LiNO_3$. We have made sure that the coolant lines are placed in an orientation which will provide natural convection. That is to say, the coolant inlets are always at the bottom of the reactor, the outlets at the top and the storage tank is located above the reactor. As long as there is a heat sink available, natural convection will take place. Since afterheat in a reactor is usually only a few percent of the normal heat load, the heat sink can be in the form of a natural air convection heat exchanger in series with the much larger water/water heat exchanger which is the heat sink during reactor operation. For such a system to operate, there is no need for active measures, rather the system becomes operational in a totally passive mode.

In the case of a LOCA transient, the situation is more complicated. Such a transient is initiated when a leak occurs in a coolant line and the coolant drains out. Natural convection of the coolant can no longer be counted on and some other means for dissipating the decay heat must be found.

Figure 1 gives the specific decay heat generation in the outboard and inboard breeding shields, as well as the sum of the two. It can be seen that the specific decay heat in the inboard shield is an order of magnitude greater on a volumetric basis than the outboard. Further, the heat capacity of the outboard shield is higher than the inboard and it therefore has a higher thermal inertia. In the next sections we examine each shield separately.

Outboard Shield LOCA Analysis

The outboard shield consists of a 40 cm zone of beryllium pebbles followed by an 82 cm zone of steel pebbles as shown in the schematic in Fig. 2. Because this shield has such a high heat capacity we have decided to analyze it initially using simple adiabatic heatup. We assume that the shield is insulated on all sides and the afterheat is absorbed by simply raising the temperature of the shield.

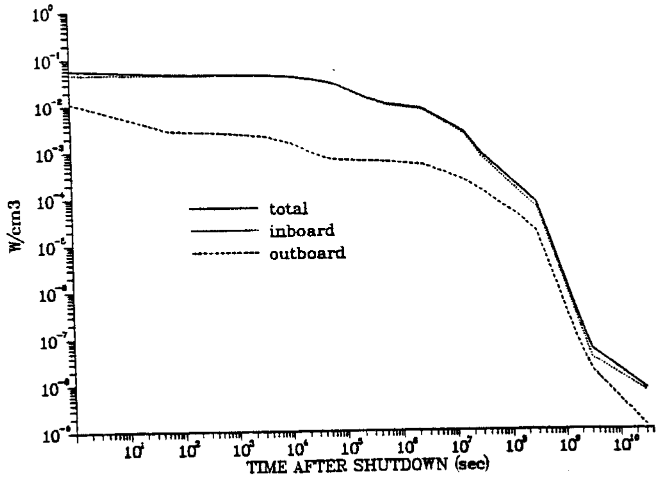

Fig. 1. Specific decay heat in TIBER-II.

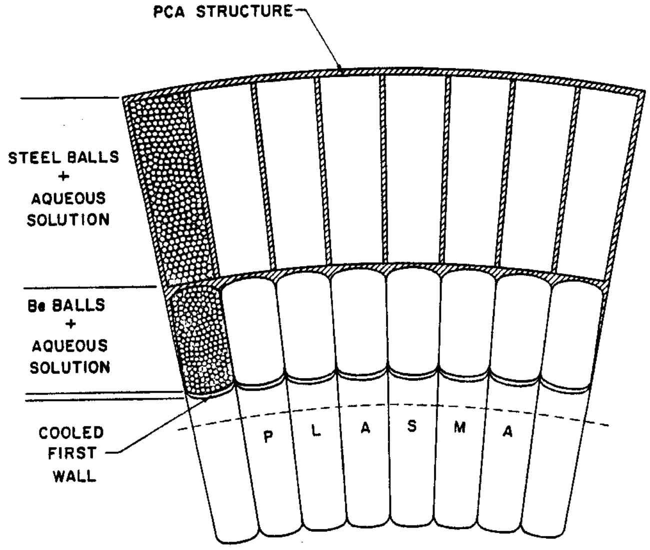

Fig. 2. Schematic of outboard breeding shield.

To calculate the temperature distribution in the shield following a LOCA we derive the effective thermal conductivity and specific heat as functions of temperature for the pebble beds, where the coolant is replaced with air at one atmosphere. For pebble beds with void fractions of 37.5%, the following relationships have been derived:

	Thermal Conductivity W/mK	Specific Heat J/kg K
Be Pebble Bed	4.4×10^{-4} T + 0.496	1.384 T + 1940
Steel Pebble Bed	4.4×10^{-4} + 0.263	0.914 T + 404

where T is in °C.

Decay heat is calculated after 2.5 full power years of operation and is available as a function of the distance into the shield [5]. Assuming the plasma stays on for 10 s, the maximum temperature of the 0.7 cm thick first wall will reach 313°C. This temperature equilibrates with the shield temperature very quickly. The average temperature rise of the shield during the 10 s burn is 16°C reaching an average value of 88°C.

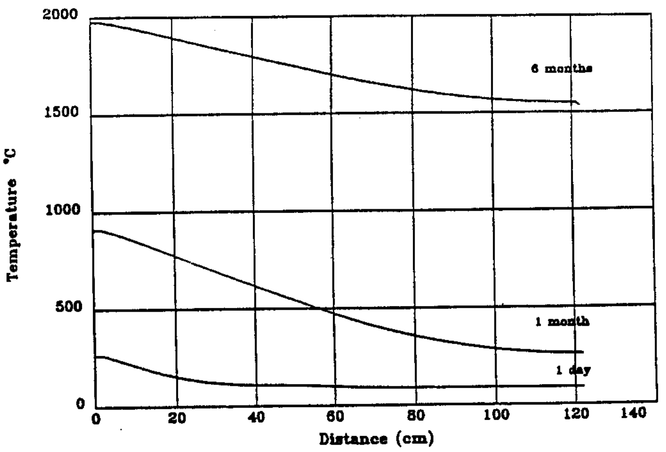

Fig. 3. Temperature history of outboard shield following LOCA assuming adiabatic heatup.

Figure 3 shows the temperature history of the outboard shield following a LOCA assuming adiabatic heatup. The temperature of the first wall reaches 250°C after 24 hours while the bulk of the shield stays around 100°C. After one month, the first wall temperature reaches 900°C. Clearly the assumption of adiabatic heatup with insulated boundaries is very conservative since in reality all the surrounding structures will also warm up. We feel that there is sufficient time before a high temperature is reached to take some active measures.

Inboard Shield LOCA Analysis

Figure 4 is a schematic cross section of a segment of the inboard shield. It is 48 cm thick, composed primarily of machinable tungsten alloy (W-2 Kennametal) zones interspersed with coolant channels. The tungsten alloy is in the form of plates oriented circumferentially and the coolant channels run vertically traversing the shield from the bottom to the top.

It is a fact of life that whenever a neutron shield is designed to be compact and highly efficient it will have high decay heat. The volumetric specific heat of the inboard shield is only 1.6 J/cm^3 K as compared to 3.1 for the Be zone and 2.9 for the steel zone in the outboard shield. The combination of these two circumstances makes the LOCA problem for the inboard shield much more serious, and adiabatic heatup is out of the question. There are several solutions that can be considered. One solution is to allow the TF coils to warm up and thus dissipate some of the decay heat. The heat capacity of metals at low temperature is quite low. If the TF coils were to absorb all the decay heat generated by the inboard shield in the first 24 hours, they would reach an average temperature of 420 K or 147°C. We can see from Fig. 1 that the decay heat starts to fall off after the first 24 hours. The specific decay heat at 48 hours is ~ 64% of its value at 24 hours, but still is very high. At best this scheme provides a reprieve of

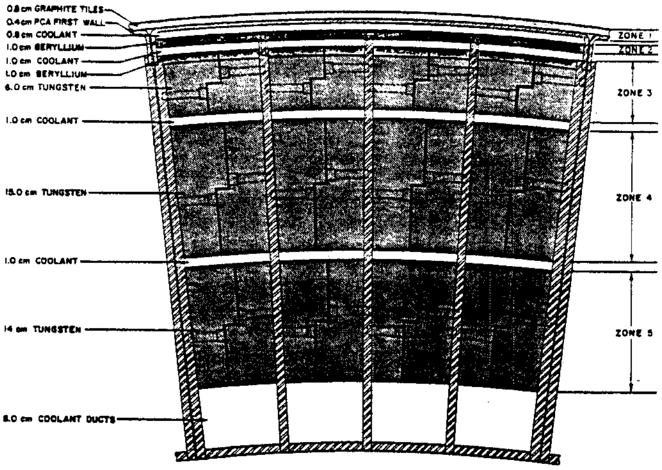

Fig. 4. Schematic of inboard shield.

about 24 hours after which some active measure must be undertaken. Another solution is to provide a 50 m^3 auxiliary tank of water located above the reactor. During a LOCA, a rupture disc would burst and the water would flow by gravity through the inboard shield. The latent heat of vaporization of the 50 m^3 water would absorb the decay heat generated in the first 24 hours. Neither of these solutions provides the long term decay heat dissipation which is needed.

The scheme that does seem to provide a long term solution is that of circulating air through the coolant channels in the inboard shield using natural convection. For this scheme to work, air would have to be admitted into the coolant lines on the bottom of the reactor and after flowing through the shield, is discharged through a stack 30-40 m high. The buoyant force generated by the heated air rising through the stack is sufficient to overcome the pressure drop through the coolant lines and the shield channels. Obviously, there are some environmental issues that must be investigated and they will be discussed later.

The code ATHENA [6], a one-dimensional thermal hydraulics code developed at EG&G Idaho, was used to calculate the temperature history of the inboard shield. The inboard shield is modelled as five heat conducting slabs and five cooling ducts running vertically between the slabs as shown in Fig. 4. The outer periphery of the shield is assumed to be adiabatic and we assume no special distribution of decay heat across any one zone. We also assume that the coolant is lost instantaneously.

In the model, air at 300 K and atmospheric pressure is admitted into the coolant lines at the bottom of the reactor, is heated by the decay heat, rises to the top of the shield through the coolant channels exiting the reactor at the top through the coolant lines and is finally discharged to the outside through a 1.0 m diameter stack 40 m high. The outside air is assumed to be 300 K and one atmosphere. To solve the problem with ATHENA we had to assume the existence of a downcomer equivalent to the stack in the system where in real life the downcomer is the great outdoors. The mass flow rate in the downcomer is identical to the mass flow rate in the stack and the temperature is constant at 300 K.

The initial average temperature of the shield after a 10 s burn with no cooling is 414 K. Figure 5 shows the average temperature of the five zones as a function of time. We can see that zone 2 is the hottest, reaching a maximum average temperature of 780 K, or 507°C, a comfortable margin lower than 600°C which is where the structural material will degrade. This temperature is reached in 3.8 hours and stays constant for another 3 hours after which it starts to decrease. All the other zones peak at average temperatures < 756 K. With the exception of zone 5, a leveling off or a downward trend in the temperature is observed after 6.7 hours into LOCA. Zone 5 which has the lowest afterheat generation and the most cooling levels off in 10 hours, reaching an average temperature of 380 K.

This analysis shows that there is an adequate safety margin in the maximum temperature reached to allow the incorporation of a filter at the point of air discharge into the stack. Such a filter would remove any solid particles which may be carried by the air stream.

Safety Implications of Air Circulation

There are primarily two safety concerns with respect to the scheme of air circulation through the inboard shield. They are: 1) potential for radioactive release to the environment through the stack and 2) consequences of air ingress into the reaction chamber. In this section we attempt to address the first issue and make some qualitative remarks about the second.

The pathways identified for release of radioactivity to the atmosphere are:

1. Corrosion product release
2. T_2 release
3. Coolant activation product release
4. Mobilization of oxides.

The radioactivity values quoted here were taken from Chapter 5 of the final TIBER-II [7] report. Table 5.2.3 in Ref. 7 gives the end of life value of 1.6 x 10^5 Ci as the radioactive corrosion product inventory in 200 m^3 of coolant, assuming that the products remain in solution and build up with no removal during the lifetime of the reactor. In actual fact, corrosion products are usually dissolved in the heated leg of the coolant loop and plate out in the cooled leg which is the heat exchanger. Corrosion products from austenitic steel consist of Ni, Cr and Mn which plate

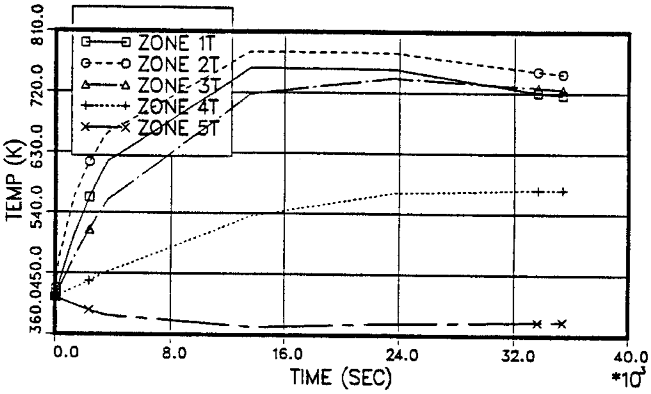

Fig. 5. Temperature history of inboard shield following LOCA using natural circulation of air.

out in the form of interconnected dendritic crystals which are very hard and tenacious, and not likely to be dislodged or carried along in a low velocity air stream. Further, the inlet to the stack could be upstream of the heat exchanger and finally, we have already mentioned that a filter can be incorporated at the inlet to the stack, thus negating these concerns.

To estimate the amount of T_2 that can be released following LOCA, we assume that all of it is in the form of T_2O or THO and we calculate the amount of coolant which is likely to hang up on the coolant channel surfaces after it is drained out. The surface area of the coolant channels is 370 m^2 and if we assume that 0.5 mm remains suspended on the walls, the total volume is 0.185 m^3. The total average T_2 inventory in 200 m^3 of coolant is 2 x 10^6 Ci, thus the fraction remaining is 1850 Ci. This release would amount to an offsite prompt dose of 0.6 mSv. Similarly, if we assume that the coolant activation product, C14 is in a dissolved form, the release of that would amount to .006 mSv. The target offsite prompt dose for TIBER is 10 mSv [7].

The last pathway is due to mobilization of oxides formed on the steel at high temperatures. Figure 6, which has been taken from the TIBER-II report [7], shows the fraction of the PCA oxide inventory mobilized from the inboard first wall as a function of temperature in 24 hours of exposure to air. For the augmented PCA it shows that 1 mSv is mobilized in 24 hours at 800°C and 10 mSv at 1100°C. We have already shown that the maximum temperature reached is < 510°C and no appreciable oxide mobilization would be expected.

The issue of air ingress into the reaction chamber is more complex and needs further investigation. The major concern is a Li fire and oxidation of the vanadium structure in some blanket test modules. For air to come in contact with Li, there must be simultaneous breaches in the inboard shield first wall and in a Li blanket test module during a LOCA. For air to react with the vanadium, a breach in the inboard first wall will be needed. To fully access the problem, the likelihood of such simultaneous events must be determined and weighed against the consequences of dealing with the LOCA issue in some other way than what is proposed in this study.

Actuation of Air Circulation System

Some questions have been raised on whether this air circulation system can be actuated passively. We believe that it can with the use of heat pipes and/or phase change pressure bulbs installed in the inboard shield, combined with some clever engineering. If that is not possible, manually operated vent hatches can be designed with access from radiation free areas. Since the cooling does not have to be started immediately after LOCA, there will be time for such action to be taken, say within the first hour after shutdown.

Conclusions

It has been shown that both inboard and outboard breeding shields in the TIBER-II reactor are inherently safe with respect to LOFA and the outboard shield with respect to LOCA. The inboard shield can be made passively safe with respect to LOCA by the use of air circulation through the coolant channels and the radioactive release to the environment appears to be within prescribed limits. There appears to be adequate safety margin to incorporate a filter at the discharge point to the stack. The implication of the potential for air ingress into the reaction chamber needs further study.

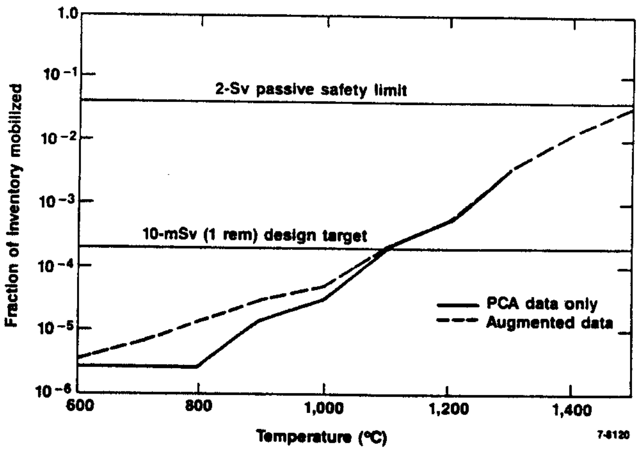

Fig. 6. Fraction of radioactivity (BHP) mobilized from inboard first wall by 24 hour exposure to air.

Acknowledgement

This research has been supported by the U.S. Department of Energy.

References

[1] L. El-Guebaly and I.N. Sviatoslavsky, "High Performance Inboard Shield Design for the Compact TIBER-II Test Reactor," University of Wisconsin, Paper #31-11, this conference.

[2] K. Hannerz, "Toward Intrinsically Safe Light Water Reactors," Institute for Energy Analysis, Oak Ridge Associated Universities, ORAU/IEA-83-2M, February 1983.

[3] Bechtel Group, Inc., "Evaluation of Small Modular High Temperature Gas-Cooled Reactors Applied to Electricity Generation," San Francisco, CA, GCRA 84-002, May 1984.

[4] W.S. Flinn, R.A. Matzie and N.L. Shapiro, "A Realistic Alternative," Proc. of ANS Annual Meeting, Boston, MA, June 1985.

[5] H. Attaya, "Activation Analysis for TIBER-II," University of Wisconsin-Madison, paper #04-03, this conference.

[6] H. Chow, P.A. Roth, K.E. Carlson and V.H. Ransom, "ATHENA Code Manual," Vol. I Draft, EG&G Idaho Report RST 7034, September 1985.

[7] J.D. Lee, technical editor, "TIBER-II/ETR Final Design Report," UCID-21150 (1987) to be published.