

# Consequences of Return to Power after a Beam Interruption in the Blanket of an Accelerator Driven System

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# Consequences of Return to Power after a Beam Interruption in the Blanket of an Accelerator Driven System

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*Abstract—A sudden drop in power after a beam interruption leads to thermal fatigue effects in structural components in the blanket of an accelerator driven system. These thermal fatigue effects limit component lifetimes. A sudden return to power after a beam interruption can contribute significant additional thermal fatigue and greatly reduce component lifetimes. One obvious solution is a gradual return to power after a beam interruption. There are two potential problems with this solution. One problem involves interruptions that are longer than the thermal time constants of thin structural members but shorter than the time constants of thick structural members. In such a case, a gradual return to power reduces the additional thermal fatigue in the thin structural members but increases the thermal fatigue in thick structural members. Some compromise is necessary. The other problem is that for thick components with long thermal time constants a long, gradual return to power is required to minimize additional thermal fatigue. Such a slow return to power can reduce the utilization or the effective load factor of the system. Specific examples of beam interruptions with various assumptions on return to power are provided for a preliminary design for the blanket of the Accelerator Driven Test Facility. Also, mitigation options to increase component lifetime are discussed. These mitigation options include improving beam reliability and modifying the blanket design to better tolerate beam interruptions.*

## I. INTRODUCTION

One problem faced by structural materials in the blanket of an accelerator driven system is low cycle thermal fatigue caused by loss of power due to beam interruptions. Thermal fatigue in the blanket of the Accelerator Transmutation of Waste (ATW) facility was discussed in References 1 and 2, but the additional thermal fatigue due to return to power after a beam interruption was only mentioned briefly in these references. The implications of return to power, and various schemes that can be used to limit additional thermal fatigue caused by return to power, are the subject of this paper. Also, mitigation of over-all thermal fatigue consequences is discussed.

The work discussed in References 1 and 2 was applied to an ATW with a blanket design based on the Advanced Liquid Metal Reactor (ALMR). In the current work the system under consideration is the 100 Mwt subcritical multiplier (SCM-100) of the Accelerator Driven Test Facility (ADTF). The SCM-100 design considered here is based on the EBR-II reactor design. Since EBR-II operated at 62.5 Mwt, and SCM-100 is intended to run at 100 Mwt, the number of core subassemblies, the pipe sizes, and the number of tubes in the intermediate heat exchanger are scaled up for SCM-100.

Because of the design differences, the areas of concern for the ADTF are somewhat different than those for the ATW. The average coolant temperature rise across

the core in the ALMR was about 139 K, whereas in EBR-II it was about 100 K. Since the temperature differences driving thermal fatigue in primary loop structures tend to be proportional to the coolant temperature rise across the core, thermal fatigue in the primary loop of the ADTF design should be somewhat lower than in the ATW design. In the ATW results, one key area of concern for thermal fatigue was the above core load pads on the subassembly duct walls above the active core. In the EBR-II design there are no above core load pads on the subassembly walls. Instead the subassembly duct walls are dimpled above the core to maintain subassembly spacing. The EBR-II subassembly duct walls are thin enough that thermal fatigue is not a concern with them. On the other hand, the EBR-II subassemblies had thick steel shielding within the subassemblies both above and below the pin section. The above core shielding is thick enough that it is a key concern in the thermal fatigue analysis.

## II. ANALYSIS METHODS

In order to analyze the consequences of a particular beam loss and return to power transient, the SASSYS-1 LMR systems analysis code<sup>3</sup> was used to analyze the transient and to obtain the time dependent temperatures of the coolant in contact with various structural components. Multi-node structure temperature calculations are then used to obtain minimum, maximum,

and average structure temperatures. The difference between the minimum or maximum temperature and the average structure temperature is multiplied by the thermal expansion coefficient to obtain the strain magnitude. The peak strain magnitude is used with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code to determine the allowable number of cycles the structural component can be subjected to. Beam reliability data for the LANSCE accelerator are used to obtain the number of beam interruptions per year of a particular duration. The integral over interruption duration of the ratio of the interruptions per year for a particular interruption duration to the allowable number of cycles of that duration gives a damage function which determines the allowable lifetime for the structural component.

### II.A. The SASSYS-1 LMR Systems Analysis

The SASSYS-1 LMR systems analysis code contains neutron kinetics coupled with a detailed thermal hydraulics treatment of the core, the primary and intermediate heat removal loops, and the steam generators. Both steady-state and transient calculations are done by the code. The neutron kinetics treatment contains point kinetics, with or without an external source. Also in the code is an optional 3-D time dependent neutron kinetics capability.

The thermal hydraulics in SASSYS-1 uses a multi-channel treatment for core subassemblies. Each channel represents one subassembly or a group of similar subassemblies. A channel models a fuel pin, its associated coolant, and structure. The subassembly duct wall is treated as structure, and wrapper wires around the fuel pins can be included in the structure. Coolant and structure above and below the fuel pin is also treated: the whole length of the subassembly from the inlet plenum to the outlet plenum is modeled. Beyond the core subassemblies the code calculates coolant pressures and flows, as well as temperatures for coolant and structure (walls). Calculations are made for inlet and outlet plenums, pipes, pumps, intermediate heat exchangers, and steam generators.

### II.B. Multi-Node Structure Temperature Calculations

SASSYS-1 calculates structure temperatures, but SASSYS-1 uses only one or two radial nodes in the structure. One or two radial nodes are not sufficient to provide accurate transient temperatures in a transient as fast as those being considered in this work. Therefore, small, separate multi-node codes TSLAB and TCYLNDR were written to calculate accurate time-dependent structure temperatures in slab and cylindrical geometries, given the coolant temperatures calculated by SASSYS-1. TSLAB

was used for components such as the subassembly duct walls and the outer rim of the intermediate heat exchanger upper tube sheet. TCYLNDR can analyze either a hollow cylinder with the coolant on the inside or a solid cylinder with the coolant on the outside. TCYLNDR was used for the above core shielding in the subassemblies and for the inner part of the intermediate heat exchanger tube sheet. For the inner part of the tube sheet, the region around a tube penetration through the tube sheet is modelled as a cylinder with an inner radius equal to the inner radius of the tube. The outer radius of the cylinder is chosen to conserve the tube sheet volume associated with one tube.

### II.C. Evaluation of Low Cycle Fatigue at Elevated Temperatures

The method used for evaluation of low cycle fatigue at elevated temperatures is based on article T-1432 of Appendix T of Subsection NH of the ASME Boiler and Pressure Vessel Code<sup>4</sup>. This type of analysis is required when the temperatures exceed 700 or 800 °F. The difference between the average structure temperature and the minimum or maximum temperature is multiplied by the thermal expansion coefficient to obtain the strain.. The peak strain for a cycle is used to obtain the allowable number of cycles that the structure can be subjected to. Figure 1 shows results for 304 stainless steel. Note that an increase of only a few degrees in peak temperature difference can lead to a decrease of a factor of two in the allowable number of cycles.

#### II.C.1. Treatment of HT-9 Steel

Evaluation of low cycle fatigue in the HT-9 steel alloy used for cladding, subassembly duct walls, and shielding in the subassemblies is a special problem. Appendix T only includes data for four materials: 304 stainless steel, 316 stainless steel, Ni-Fe-Cr alloy 800H, and 2 1/4 Cr-1 Mo steel. Furthermore, there appears to be no low cycle fatigue failure data anywhere for HT-9. What is done in this work is to evaluate HT-9 as if it were 316 stainless steel and then divide the allowable number of cycles by an uncertainty factor. In order to estimate the uncertainty factor, the ASME low cycle fatigue treatment in Subsection NB of Section III is used. This treatment is limited to temperatures below 700 - 800 °F; but it is applicable to broad classes of steels, including one category for ferritic steels and another category for austenitic steels such as 316 stainless steel. Using this treatment the allowable number of cycles for the austenitic category tends to be about six times as great as the allowable number of cycles for the ferritic category with the same temperature difference. Therefore, a value of six is used for the uncertainty factor.

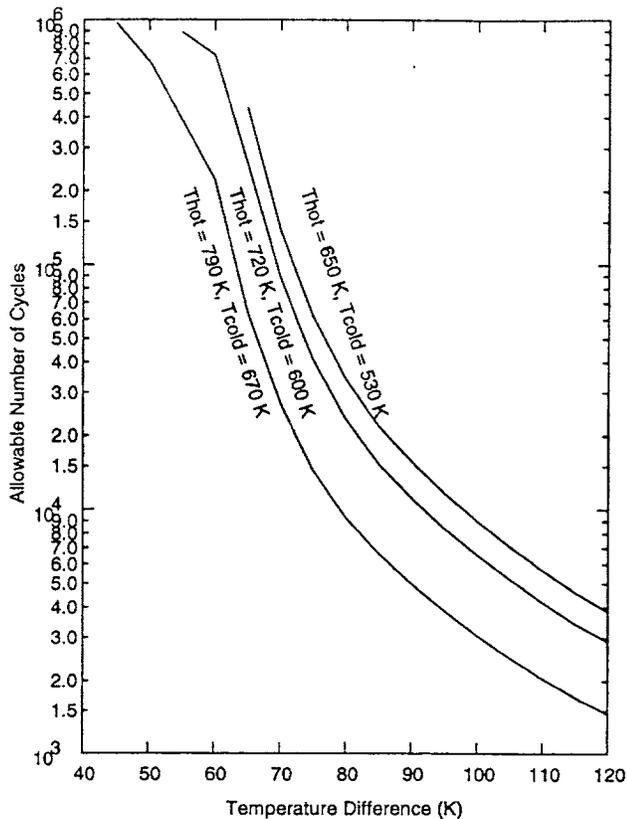


Fig. 1, ASME Thermal Fatigue Results

#### II.D. LANSCE Data for the Accelerator Beam Interruption Frequency

Figure 2 shows the data obtained by Eriksson<sup>5</sup> for the frequency of beam interruptions of various durations in the LANSCE accelerator. This data is used in determining component lifetime.

#### II.E. Calculation of Component Lifetime for a Spectrum of Interruption Durations

In order to evaluate the allowable component lifetime, a damage rate,  $d$ , is used to give the damage per year. The allowable lifetime is  $1/d$  years. To evaluate the damage rate for a wide range of interruption durations, the interruption durations are grouped into intervals. Interval  $I$  includes interruptions with down times from  $t_{di}$  to  $t_{di+1}$ . Then the damage rate is given by

$$d = \sum I_i/A_i$$

where

$A_i$  = allowable number of cycles for interruptions in interval  $I$ , and  
 $I_i$  = interruptions per year in interval  $I$ .

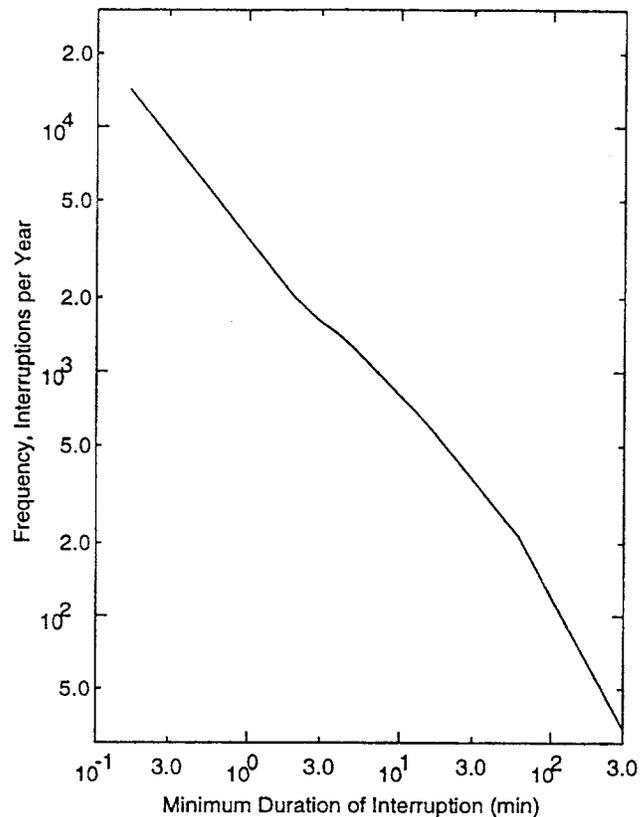


Fig. 2, LANSCE Beam Interruption Data

### III. RESULTS OF BEAM INTERRUPTIONS AND RETURN TO POWER

For the ADTF design considered here, the two areas that have been identified as being of concern for thermal fatigue are the outer rim of the upper tube sheet, beyond the tube penetrations, in the intermediate heat exchanger (IHX) and the upper shielding within the core subassemblies. Other structural components have been investigated and found to be able to survive significantly more interruptions than these two components.

#### III.A. Results for Various Return to Power Ramps

Figure 3 shows the structure temperature differences responsible for thermal fatigue in the above core shielding due to a beam interruption of 10 seconds followed by a ramp back to power. The temperature difference in Fig. 3 peaks at a value of 73.8 K at 1.4

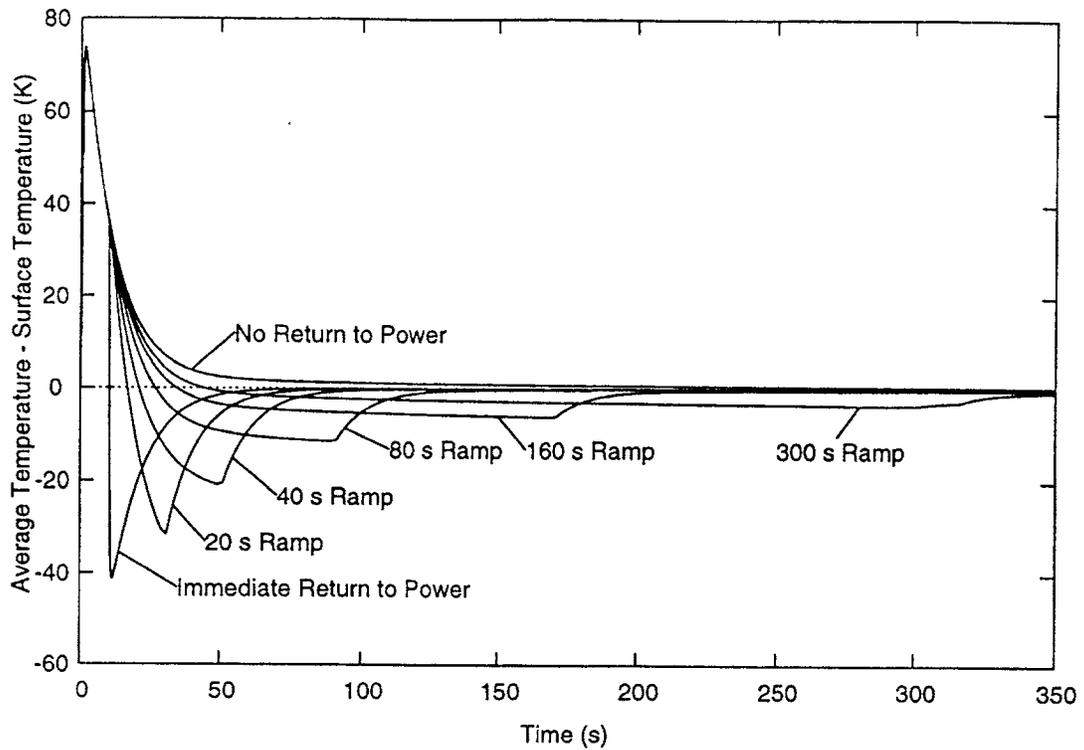


Fig. 3, Structure Temperature Differences in the Above Core Shielding Due to a Beam Interruption of 10 Seconds, Followed by a Ramp Back to Power

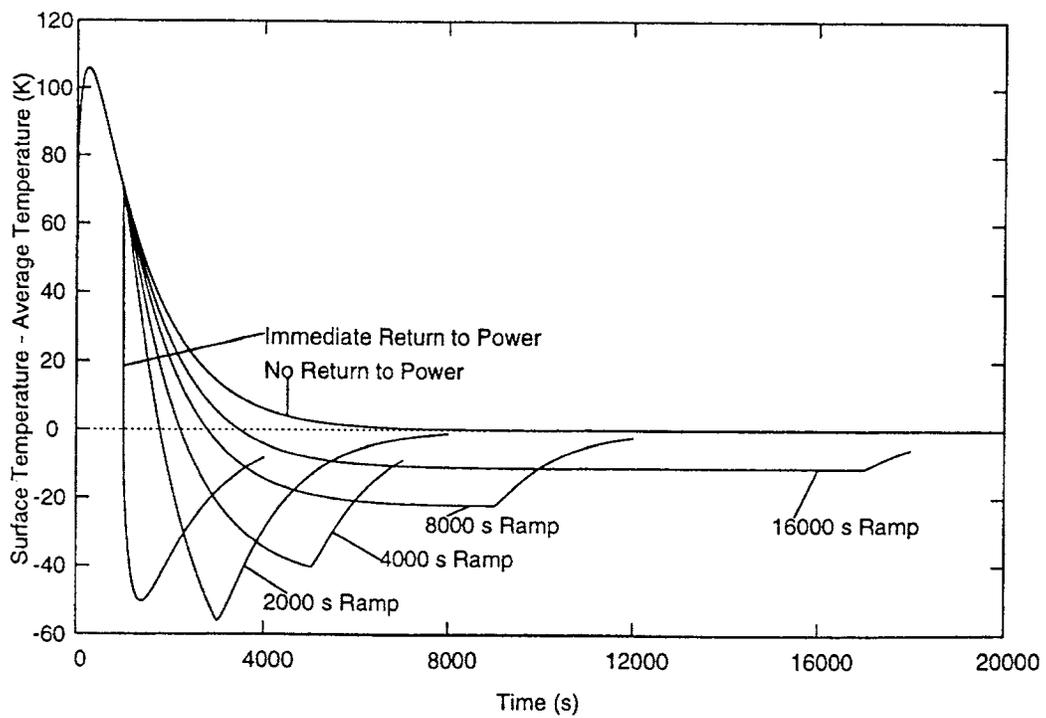


Fig. 4, Structure Temperature Differences in the IHX Tube sheet Rim Due to a Beam Interruption of 1000 Seconds, Followed by a Ramp Back to Power

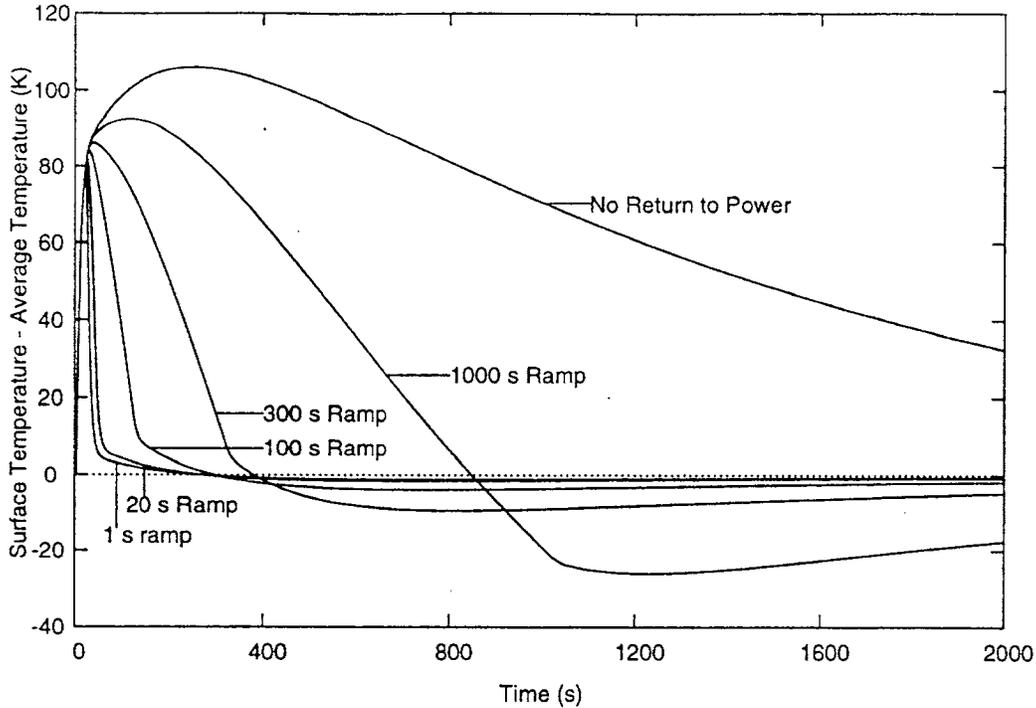


Fig. 5, Structure Temperature Differences in the IHX Tube Sheet Rim Due to a Beam Interruption of 20 Seconds, Followed by a Ramp Back to Power

seconds after the beam interruption. An immediate return to power at 10 seconds gives a negative peak of -41.2 K at 11.6 seconds. This gives a total peak-to-peak difference of 115 K. The total peak-to-peak difference is the relevant temperature difference that enters into the thermal fatigue calculation. The contribution of the negative peak decreases with increased ramp time.

Figure 4 shows the structure temperature differences in the IHX upper tube sheet rim due to a beam interruption of 1000 seconds followed by a ramp back to power. An immediate return to power at 1000 seconds leads to a negative peak of -50 K at 1395 seconds into the transient. The contribution of the negative peak decreases with increased ramp length, but even with a ramp time of 16,000 seconds the size of the negative peak is -11 K. Thus, for a beam interruption as long as 1000 seconds, the return to power has to take hours in order to avoid significant additional thermal fatigue in the IHX upper tube sheet rim.

In Fig. 4, the peak in the temperature difference for the IHX tube sheet rim occurs at 250 seconds, and the return to power occurs later. Figure 5 shows results for a different IHX tube sheet rim case. In this case, the return to power starts at 20 seconds, which is well before the peak. For this case an immediate return to power or a short return to power ramp produces less thermal fatigue than a long ramp.

### III.B. Return to Power Schemes

In specifying the return to power after a beam interruption, there is a conflict between protecting the shielding above the core in the subassemblies and protecting the IHX tube sheet rim. Temperature differences in the shielding peak 1.4 seconds after an interruption, but temperature differences in the IHX tube sheet rim do not peak until 250 seconds after the interruption. For an interruption with a duration greater than 1.4 seconds but significantly less than 250 seconds, after the interruption one would want to return to power slowly to minimize the additional thermal fatigue in the above core shielding; but one would want to return to power quickly to minimize the peak temperature difference in the IHX tube sheet rim. Some compromise must be made. Results obtained with two different return to power schemes are presented below to quantify the effects of this conflict.

The two different return to power schemes are shown below. The difference between these two schemes is that for short interruptions the ramp time in scheme B is 100 seconds instead of 300 seconds. Thus, scheme A provides more protection to the above core shielding, whereas scheme B provides more protection to the IHX upper tube sheet rim.

#### Scheme A for Return to Power After a Beam Interruption

|                             |  |
|-----------------------------|--|
| interruption < 1 second,    | return to power immediately, if possible   |
| 1 s ≤ interruption < 50 s   | ramp time = 300 seconds for return to power  |
| 50 s ≤ interruption < 400 s | double ramp, 0 - .75 power in 300 seconds,<br>.75 - 1.0 power in 8000 more seconds |
| interruption ≥ 400 s        | ramp time = 16,000 seconds   |

#### Scheme B for Return to Power After a Beam Interruption

|                             |  |
|-----------------------------|--|
| interruption < 1 second,    | return to power immediately, if possible   |
| 1 s ≤ interruption < 50 s   | ramp time = 100 seconds for return to power  |
| 50 s ≤ interruption < 400 s | double ramp, 0 - .75 power in 100 seconds,<br>.75 - 1.0 power in 8000 more seconds |
| interruption ≥ 400 s        | ramp time = 16,000 seconds   |

Table 1, Component Lifetimes, Impact of Return to Power Scheme

| component                | lifetime (years), ignoring temperature overshoot from return to power | lifetime (years), scheme A | lifetime (years), scheme B |
|--------------------------|---|----------------------------|----------------------------|
| IHX upper tube sheet rim | 1.01  | .48                        | .69                        |
| above core shielding     | .40   | .26                        | .15                        |

With these two return to power schemes, and with the LANSCE interruption data, the component lifetimes are as shown in Table 1.

#### IV. MITIGATION MEASURES

The component lifetimes in Table 1 are unacceptable. The subassemblies are left in the core for three or four years, so an above core shielding lifetime of at least three or four years is required. The lifetime of the IHX should be at least as long as the expected operational lifetime of the plant, although replacing the IHX once during the plant lifetime may be acceptable. Replacing the IHX would be expensive. Thus, some mitigation measures need to be taken to reduce accelerator beam interruptions and/or to increase the tolerance of the blanket to beam interruptions.

A significant reduction in the frequency of beam interruptions should be possible. The LANSCE accelerator is an old accelerator. A new accelerator built with modern technology would be expected to be more reliable by a factor of ten or more. A factor of ten increase in component lifetime would be helpful but not sufficient. Additional improvement is necessary.

Increasing the tolerance of the blanket to beam interruptions requires design changes. Either the

thicknesses of critical structural materials must be reduced or transient temperature changes must be reduced. An example of a SCM-100 design in which the transient temperature changes are reduced is given below.

#### V. A BEAM INTERRUPTION TOLERANT DESIGN

The results presented here so far were for a SCM-100 design which is basically the EBR-II reactor scaled up from 62.5 MwT to 1000 MwT by increasing the number of subassemblies and increasing the number of tubes in the IHX. The average coolant flow per subassembly and the average power per subassembly were approximately the same in the scaled up version. Also, the coolant temperature rise across the intermediate side of the IHX was similar. In the upper tube sheet rim of the IHX, the magnitude of the temperature perturbations caused by a beam interruption depends mainly on the IHX intermediate side coolant temperature rise. On the other hand, the magnitude of the temperature perturbations in the above core shielding depends mainly on the primary coolant temperature rise across the blanket subassemblies. Therefore, in the modified, more tolerant SCM-100 design both the primary and the intermediate coolant flow rates were increased to reduce coolant temperature rise.

Table 2, ADTF SCM-100 and EBR-II Design and Operating Parameters

|  | EBR-II (SHRT-17) | SCM-100, Original | SCM-100, Modified |
|--|------------------|-------------------|-------------------|
| power (MwT)  | 62.5             | 100               | 100               |
| average coolant temperature rise in the core (K)         | 97               | 101               | 81                |
| peak coolant temperature rise in hottest subassembly (K) | 132              | 120               | 96                |
| IHXs   | 1                | 1                 | 2                 |
| tubes per IHX  | 3248             | 5197              | 3248              |
| active length of IHX (m)                                 | 3.16             | 3.16              | 3.16              |
| IHX intermediate flow /primary flow                      | .71              | .68               | 1.0               |
| temperature rise across intermediate side of IHX (K)     | 139              | 148               | 81                |
| primary centrifugal pumps                                | 2                | 2                 | 2                 |
| intermediate pumps                                       | 1                | 1                 | 2                 |
| pump head, primary (bar)                                 | 3.22             | 2.93              | 4.20              |
| pump flow, primary (Kg/s/pump)                           | 242              | 409               | 511               |
| pump head, intermediate (Kg/s/pump)                      | 3.64             | 4.68              | 7.93              |
| pump flow, intermediate (Kg/s/pump)                      | 326              | 528               | 482               |

Table 2 lists some of the relevant design and operating parameters of the modified SCM-100. Parameters for the original design and for EBR-II at the time of the SHRT-17 test are also listed for comparison. For the modified design, the total power and the number of driver subassemblies were held constant while the coolant flow per subassembly was increased about 25%. The same thermal fatigue result could have been achieved by holding the total power and the coolant flow rate per subassembly constant and increasing the number of driver subassemblies by about 25%.

In order to make use of the spare EBR-II IHX, two EBR-II IHXs were used in the modified design. The original design used one new IHX similar to but larger than the EBR-II IHX. It would probably be possible to achieve satisfactory thermal fatigue results with a single EBR-II IHX if the total primary and secondary coolant flows were the same as in this modified design, but the IHX pressure drops would be much higher. Thus, there may be a trade-off between paying more money for IHXs or paying more money for larger pumps.

Table 3 lists the component lifetimes for the modified SCM-100 design, using Eriksson's beam interruption frequency results. Results for the original design are also listed for comparison. The above core shielding lifetime of 4.9 years should be adequate, since subassemblies are normally replaced after three or four years. The upper tube sheet rim lifetime will be adequate if there is any significant improvement (a factor of two or more) in beam reliability.

Table 3, Structural Component Lifetimes

| Component                | Lifetime (years) original design | Lifetime (years) modified design |
|--------------------------|----------------------------------|----------------------------------|
| IHX upper tube sheet rim | .48                              | 12.9                             |
| above core shielding     | .26                              | 4.9                              |

## VI. CONCLUSIONS

The return to power after a beam interruption can add significantly to thermal fatigue and can reduce component lifetimes significantly. There is no one return to power scheme that provides optimum protection for all structural components. Furthermore, any return to power scheme that minimizes additional thermal fatigue in thick structural components, such as the IHX upper tube sheet rim, requires a slow return to power over a period of hours in case of a long beam interruption. Such a slow return to power reduces the effective load factor of the system.

A new accelerator built with modern technology should be considerably more reliable than the LANSCE accelerator. If the improvement in accelerator is not sufficient to give acceptable structural component lifetimes, then the SCM-100 design can be modified to make it more tolerant to beam interruptions. The required design modifications are in the direction of increased coolant flow to reduce coolant temperature rises in the primary and intermediate coolant loops.

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