ASSESSMENT OF THERMAL SHOCK ATTENUATION IN THE PARTICLE BED OF THE SPALLATION NEUTRON SOURCE COLLIMATOR

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Abstract

A thermal shock analysis in a particle bed that surrounds the Spallation Neutron Source (SNS) beam tube in the various collimation locations is performed using a detailed thermal/stress wave propagation formulation. The goal of this effort is to assess the response of the particle bed when subjected to the full proton beam under off-normal operating conditions and its ability to attenuate the induced stress shock. Conclusions are drawn on the basis of comparison between the responses of (a) the individual particle bed elements, (b) an arrangement of elements comprising the particle bed and (c) an equivalent porous-less material with the density of the particle bed.

1 INTRODUCTION

Integral part of the SNS collimator design is a packed sphere particle bed that surrounds the proton beam tube. The main function of the particle bed is the interception of the beam halo protons. Depicted in Figure 1 is the layout of the collimator arrangement. Shown is the beam tube/particle-bed interface with de-ionized light water flowing through the pores of the particle bed removing heat due to energy deposition. Under normal operating conditions about 0.1% of the beam (2 kW) will be intercepted and stopped within the bed. The 2 MW proton beam has a frequency of 60 Hz and pulse duration of 1 μs. In the RTBT line the proton beam bunches have attained peak energies of 1.3 GeV. In the event of beam straying from the designed orbit the full proton beam rather than its halo will penetrate the beam tube and be intercepted by the particle bed. It has been conservatively assumed that two pulses will deposit energy in the bed before the beam is tripped. If such a scenario is anticipated to occur frequently then the integrity of the particle bed or whatever material in its place need to be assessed since it will resemble a target for a couple of pulses. The ability of the particle bed arrangement to diffuse and attenuate the generated thermal shock waves is the principle goal of this effort. Specifically, the analysis attempts to evaluate and compare the following alternatives: (a) a single element of the particle bed (disk or sphere) interacting with the incident proton beam, (b) an arrangement of compacted spheres (or disks) interfacing between them through contact surfaces and treated as a porous solid and (c) a particle-bed equivalent continuous material. In the latter two alternatives the beam spot and energy deposition is the same as in the case of the single solid sphere. By analyzing the three cases the severity of the generated stresses can be estimated as well as the potential for stress relief/attenuation through the non-linear contact between the individual spheres of the particle bed.

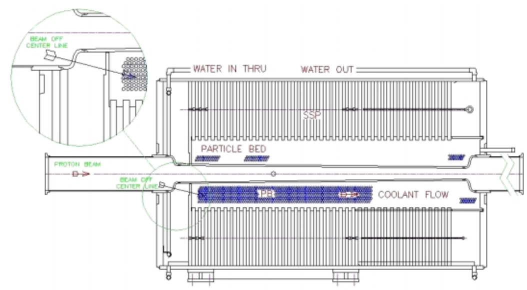


Figure 1. SNS Collimator layout and particle bed arrangement

Over the years a number of studies both analytical and experimental attempted to address the issue at hand both for individual elements of the particle bed and for the overall assembly. What needed to be answered for individual elements is their ability to withstand the high thermal shock stresses mainly for potential use in target schemes. For the overall assembly the answers sought were the effect on the speed of sound and the attenuation of the propagating stress front.

2 SHOCK ANALYSIS

To address the problem at hand a simplified version was adapted as first step in order to save on computational cost. Specifically, instead of spheres comprising the particle bed an assembly of disks was used. It is expected that if the principle of stress wave propagation and attenuation holds for the disk assembly it will also hold for the spheres. Both thermal and dynamic stress analyses were performed using the ANSYS finite element code. Fine modeling allowed for the capturing of both the diffusion and the dynamic stress propagation.

2.1 Thermal Diffusion Analysis

The thermal transient induced by the proton beam was evaluated first. Shown in Figure 2 is the proton beam spot chosen for this analysis. Specifically, the central disk in the assembly was partially heated so that the diffusion of the heat load and the stress propagation could be clearly observed. It was assumed that the heated area thermalizes instantly. The deposited heat load of 450,000 Btu/sec-in^3/pulse was estimated from neutronic calculations and the SNS proton beam parameters. Conduction and convection from the coolant flowing in the pores carried the heat away from the affected zone. Figure 3 depicts the transient temperature profile at the end of the two beam pulses. It is apparent that the heated area has not been relieved by thermal diffusion in the time interval between pulses. The generation and propagation of thermal stresses on the other hand come into play immediately.

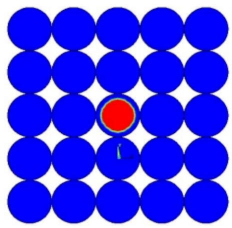


Figure 2. Particle Bed Assembly and Proton Beam Spot

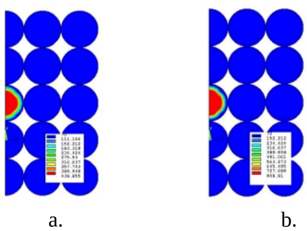


Figure 3. Temperature distribution after the first and second pulse

2.2 Elastic Shock Waves in Single Element

Shown in the different frames of Figure 4 is the stress intensity distribution at different times within a 20-pulse long interval after the beam pulse. It is interesting to note the evolution of the stresses near the center of the disk where peak stresses are experienced due to focusing of the wave front. Figures 5 and 6 depict the time variation of the hoop and radial stresses in the disk within the 20-pulse time. It is apparent that the stress wave front traverses the disk diameter a number of times while no significant diffusion has taken place in the heated zone. The initial stress in the heated zone of

$\sigma_{init} = \alpha\Delta T\ E/(1-2\nu) \cong 150$ Ksi almost doubles when the stress waves generated at the edge of the heated zone arrive at the center of the disk either directly or after reflecting from the free edge and changing sign. Because no material damping has been assumed, minimal attenuation is observed as the waves go back and forth between the center and the edge of the disk. The concern of high stresses experienced at the center of the disk is quite serious. From a theoretical standpoint the disk center represents a stress singularity. The dynamic finite element analysis reveals that stresses are expected to increase by approximately a factor of 2. It should be noted that such loads are forbidding for typical materials even after a single beam pulse of the SNS intensity. The hope will be that a spherical particle of the same size will lead to a smaller dynamic stress factor. Further, it is anticipated that the interaction of the heated disk or sphere with the surrounding disks will allow for some energy to be lost in the non-linear interfaces and some to transfer to the surrounding medium rather than it all reflect back toward the disk center.

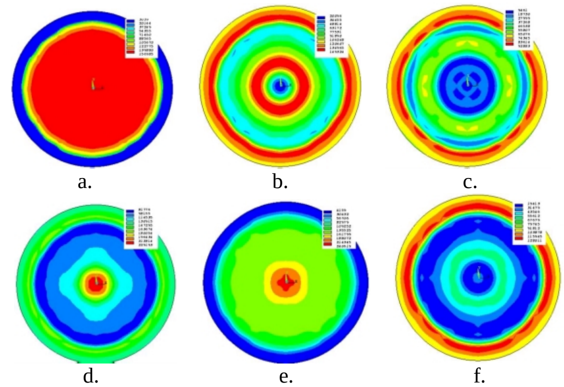


Figure 4. Stress profiles in the heated disk at different times after the first pulse

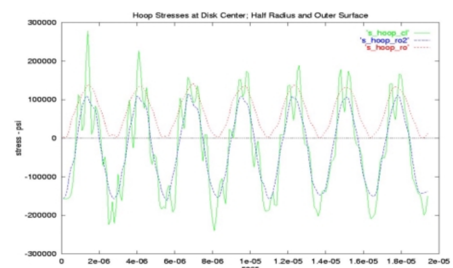


Figure 5. Hoop stress variation in a single disk. Results are shown (a) at center, (b) half-radius, and (c) outer boundary

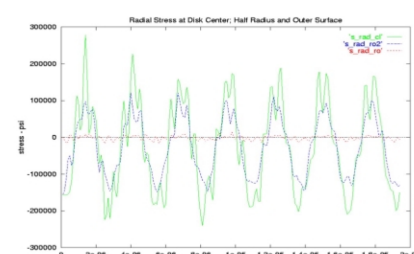
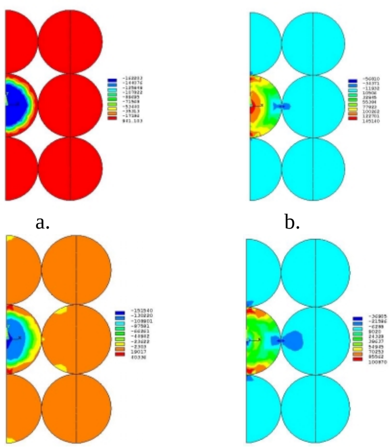


Figure 6. Radial stress variation in a single disk at same locations as in Figure 5.

2.3 Stress Attenuation in Assembly

Presented in this section are preliminary results of the stress propagation and attenuation in an assembly of disks. In order to capture the transfer of compressive loads between disks as the elastic waves reach the outer boundary a very intricate contact-of-surfaces model is implemented. The model, which is not described here due to lack of space, allows one-directional stress paths at several points where disks come into contact. No friction between the disks is accounted for. The attenuation of the stress waves that want to return to the center of the heated disk only comes from the energy transfer through the contact points. Due to the higher computational cost associated with this non-linear analysis, a smaller assembly than the one used in the heat diffusion calculations was used. Similar loading conditions as those of the single disk also applied in the disk assembly. Figure 7 depicts the initial and attenuated stresses at different times after the beam pulse.



a. b.

c. d.

Figure 7. Stress Wave Propagation in an Assembly

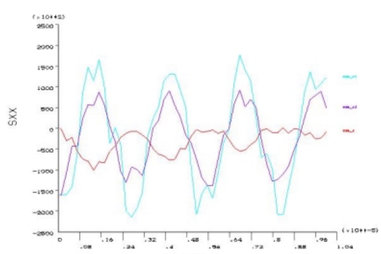


Figure 8. Stress Variation in Heated Disk

This preliminary disk assembly analysis demonstrates that a significant reduction in the stress at the center of the heated disk can be achieved simply as a result of the non-linear interaction with surrounding disks. It appears that hardly any amplification of the stresses occurs as they reflect at the boundary and converge toward the center of the disk.

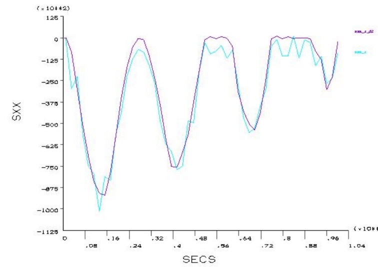


Figure 9. Radial stress at two sides of the contact surface between disks

The outgoing compressive wave simply reflects at the edge and returns as a tensile load summing up at the center to no more than the original compressive load.

3 CONCLUSIVE REMARKS

Seen from the results of this preliminary analysis, significant reduction of the stress level can be achieved by using the concept of a particle bed. While this analysis is still preliminary and uses a disk rather than a sphere assembly to draw the conclusions, the basic principle, if proven true with further scrutiny, should hold. As it applies to the SNS collimator, the main concern will be the survival of the bed to the load from a single pulse. Furthermore, the potential of using a particle bed as a beam target may look very attractive. Further studies and analysis will take place in the near future including the evaluation of a continuous material of equivalent density to the particle bed.

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