EXPERIMENTAL STUDIES ON ATTENUATION OF PRESSURE WAVES INDUCED BY THERMAL SHOCK

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ABSTRACT

High magnitude pressure waves are expected in the mercury-filled Spallation Neutron Source target system. An appropriate measure is needed to protect the target system from such high pressure waves. It has been known that inclusion of devices like scattering centers in the pressure field will attenuate pressure waves by scattering waves between scattering centers. A series of experiments have been conducted to test such a concept. After verifying the concept by performing simple scoping experiments, fives series of experiments were conducted with various configuration to measure changes in sound speed and pressure amplitude with inclusion of various scattering centers. Results indicate that for the conditions of our test, no significant change in sound speed was observed; however, substantial attenuation of pressure waves was detected with scattering centers in mercury.

INTRODUCTION

In the Spallation Neutron Source (SNS)[1], the interaction of the energetic proton beam with the mercury target can lead to very high heating rates. The rate of temperature rise in the mercury target is $\sim 10^7$ °C/s during the very brief beam pulse (~0.58 μs). The resulting thermal-shock induced compression of the mercury leads to the production of large amplitude pressure waves in the mercury that interacts with the walls of the target and the bulk flow field[2]. Safety-related operational concerns exist in two main areas. They are: (1) possible target enclosure failure from impact of thermal shocks on the wall due to its direct heating from the proton beam and the loads transferred from the mercury compression waves, and (2) impact of the compression-cum-rarefaction wave-induced effects such as cavitation bubble emanation and fluid surging. Therefore, development of an appropriate engineering design or features to minimize such loads to the target system is important for this project.

OBJECTIVES

Bubbles induced from cavitation and/or artificial devices featuring scattering centers (SCs) in the mercury could provide substantial attenuation of thermal-shock induced pressure waves. The general mitigation approach relies on wave energy attenuation via use of appropriately-configured SCs in the bulk or at liquid-structure interface regions. Objectives for this series of experiments are to investigate the various SCs for their effectiveness in causing pressure wave attenuation by measuring velocity of wave propagation in the bulk medium composed of mercury and SCs, and reduction in amplitudes of pressure waves traveling through such a medium. Preliminary results of experiments and analysis on effectiveness of SCs in attenuating pressure waves were reported elsewhere[3,4], and a companion paper[5] describes analytical study of the effectiveness of SCs of various configurations in a mercury-filled system.

SCOPING STUDY

Prior to conduct of detailed acoustic property measurement experiments, a series of experiments were conducted to evaluate the role of SCs on wave attenuation. This scoping study had the goal to assess and confirm the relative roles of: (1) low impedance SCs distributed in mercury and water, and (2) large impedance SCs distributed in a relatively low impedance liquid. The experiments were designed to provide quick-turnaround data for demonstrating the impact and power of the use of SCs on wave energy attenuation. This was motivated by the need to assure that reasonable confidence could be derived for motivating the implementation of such devices in the SNS target design and for integral studies with direct proton beam energy deposition. As such, a simple experimental setup was required. The setup consists of a plastic dish (with a 9cm x 13cm cross-section) filled with a chosen working fluid. At one end is an ultrasonic driver tip (12.5 mm diameter) which can deliver acoustic energy (up to several hundred watts in steps) at a drive frequency of 20 kHz. At the other end of the reservoir a pressure transducer is affixed with its measuring face submerged in the working fluid. The ultrasonic driver tip and the pressure transducer are located mid-way between the bottom and free surface of the working fluid.

Figure 1 shows SCs affixed to a plastic cover. The SC materials were chosen to be either plastic or stainless steel. The SC tube dimensions (capped at either end to provide for an air-filled space throughout the length) were nominally, 6.35mm outer diameter (OD), and 3.5mm inner diameter (ID). These relative dimensions introduce an air void fraction of ~ 1v/o (based on the tube ID), and a total mercury or water displacement void fraction of ~ 4v/o (based on the tube OD).

After filling the reservoir with the chosen working fluid to a given depth, the experiments were conducted by gradually increasing acoustic power and noting the wave form of pressure variations from the pressure transducer. At each power level experiments were conducted first without any SCs, followed by introduction of plastic SCs and then with stainless steel (SS) SCs.

It is clearly seen from Figure 2 (with mercury as working fluid) that the introduction of SCs has a very significant influence on attenuating the pressure wave energy introduced by the ultrasonic driver. Reductions of 90% and greater were observed. A similar reduction was obtained with water as working fluid in Figure 3; however, SS SCs give rise to relatively modest reductions in wave energy attenuation compared with plastic SCs, where the wave energy attenuation is smaller.

The above-mentioned results reveal the following important physics-related characteristics:

1) Using SCs of the geometry used in this study where the material is of lower (or comparable) impedance than the working fluid can give rise to very significant rarefaction-type scattering-induced attenuation. This is clearly evident from results of attenuation with plastic or SS SCs in mercury, and use of plastic SCs in water.

2) Using SCs of the geometry used in this study where the material is of significantly higher impedance than that of the working fluid can give rise to only modest, or little wave energy attenuation which is governed by compression-wave scattering. This was clearly evident from results of attenuation with SS SCs in water. The lesson here pertains to the possible suggestion of using materials such as hollow tungsten cylinders in the SNS target.

The above-mentioned results provide encouragement that the suitable use of SCs in mercury targets may become a possible means for reducing or eliminating deleterious thermal-shock effects. Systematic studies are planned to incorporate this concept to the real SNS target system, and described in a later section.

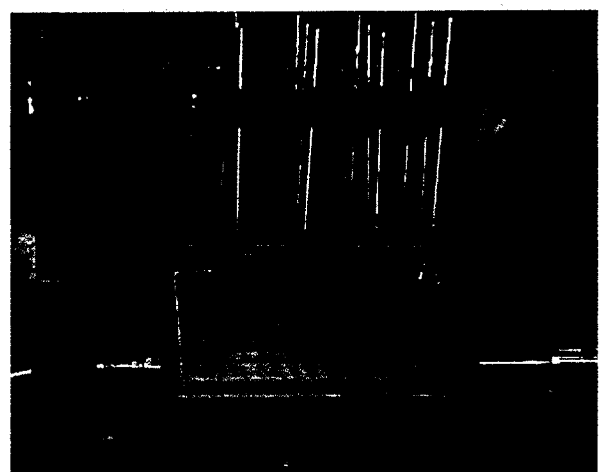

Figure 1 Test section geometry (with stainless steel tube SCs about to be placed into mercury as the working fluid)

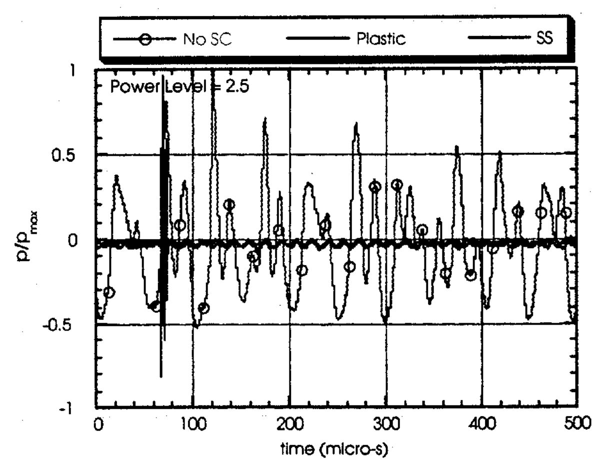

Figure 2 Wave forms with and without SCs in mercury

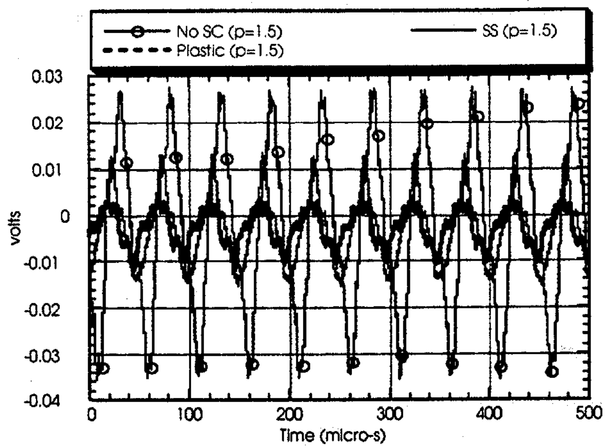

Figure 3 Wave forms with and without SCs in water

EXPERIMENT DESIGN FOR ACOUSTIC PROPERTY MEASUREMENTS

The diagram of the electronic circuitry used is illustrated briefly in Figure 4. The system consists of a plastic dish filled with a chosen working fluid (i.e., water or mercury). In the plastic dish, two piezoceramic crystals are placed a fixed distance apart. The transmitting crystal emits waves driven by a wave generator at various frequencies assisted by power amplifiers. The output of the wave generator triggers the scope and the signals are viewed on the scope. The receiving crystal converts the pressure (or sound) wave into electrical energy that can be fed to a calibrated amplifier and noise filters, if necessary, and the receiving signals are seen on the same scope with a set delay. The amount of shift along the time scale is a measure of the change in phase velocity; therefore, phase velocity can be evaluated via dividing the distance between wave transmitting and receiving crystals by the time shift between two signals shown on the scope. The amount of change in amplitude of the signals is, further, a measure of the wave energy attenuation. If a signal amplifier is to be used, the amplifier has to be calibrated to a known size of wave in order to be correctly factored as attenuation.

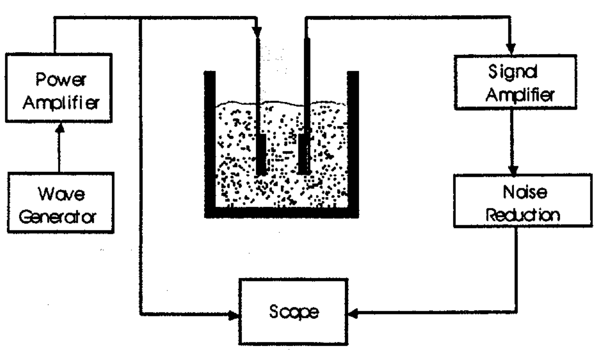

Figure 4 Block diagram of electronic apparatus

A small plastic dish (9cm x 9cm x 8.2cm) was chosen as a mercury container as seen in Figure 5. With appropriate positioning of the transmitter-cum-receiver system, for the wave interaction with surrounding structures of the container, the container size becomes unimportant. This is because we do not measure a continuous wave but measure only the first wave emitted from the transmitter and the first wave arriving at the receiver.

A sonar device for under-liquid operation was developed to generate appropriate pressure wave pulses driven by electronic devices controlling the wave pattern and frequency. A similar design was used for the receiver that detects wave variations by sending electrical signals to the scope for analysis. The major part of this device is a piezoceramic disk that is contained in a sealed perspex plastic container, electrically isolated from a conducting medium like water or mercury where this device is to be placed in. This piezoceramic disk (19mm dia. and 3.2mm thick) is made of Lead Zirconate Titanate.

Figure 5 shows that the transmitter and receiver are about to be placed into the mercury bath. Distance between two sonar devices is controlled by supporting arms attached on the back side of each sonar device, and was maintained to be 6cm throughout all the experiments. Instruments and acquisition system was composed of a function generator, a power amplifier, an oscilloscope and notebook computer for data downloading.

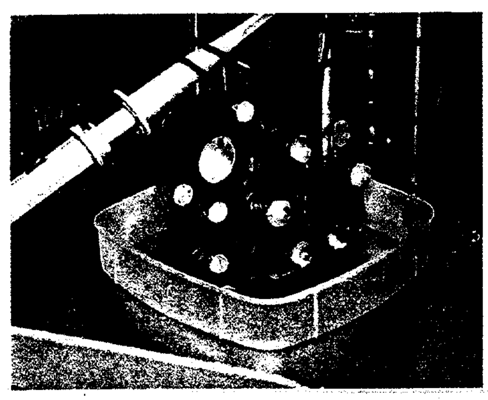

Figure 5 Mercury container with wave transmitter and receiver about to be placed in the container

EXPERIMENT PROCEDURE

Before testing with mercury, experiments were initiated in water. The system was tuned while working with water to minimize electronic noise by providing appropriate grounding to various parts of the system.

Appropriate grounding was crucial for obtaining clear data. Experiments with substantial pressure wave attenuation required unnecessary noisy traces to be totally eliminated or minimized to guarantee a meaningful detection of attenuated signal at the receiver. Most of noise was found to originate from electrostatics, and thus providing appropriate grounding successfully minimized it. Also, testing with water was performed to build experience in handling and tuning the system at various frequencies and amplitudes. To distinguish the first signal detected by the receiver from scattered waves or rarefaction waves from surrounding structures, the wave function generator was programmed to produce a single wave with various pulse widths and amplitudes instead of producing multiple continuous waves at a set frequency. Various patterns of waves were investigated, and a square wave was chosen as a transmitting wave pattern since it was observed to give the most clean wave patterns detected by the receiver. After adequate experience with the water system was obtained, experiments with mercury were conducted for various conditions.

Two basic parameters were measured during experiments. They are sound speed and wave attenuation. Sound speed was calculated by dividing the transit distance (6cm in most of the experiments) by the transit time of the wave from the transmitter and the receiver. Wave attenuation was measured by comparing amplitude of the first wave detected by the receiver for mercury without SCs against that of the mercury system with various SCs.

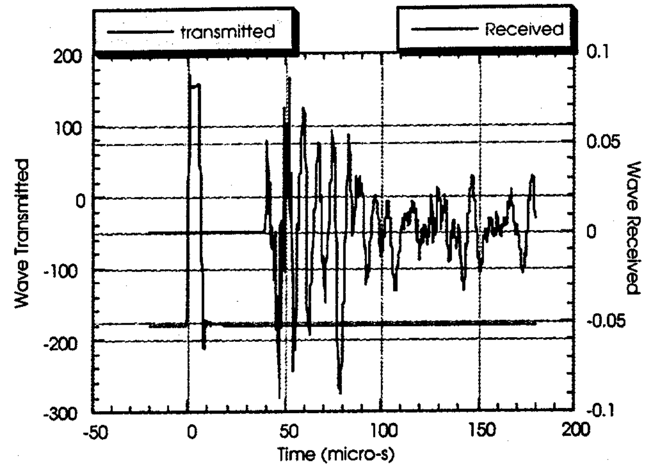

Figure 6 Typical transient data Measured for waves transmitted and received

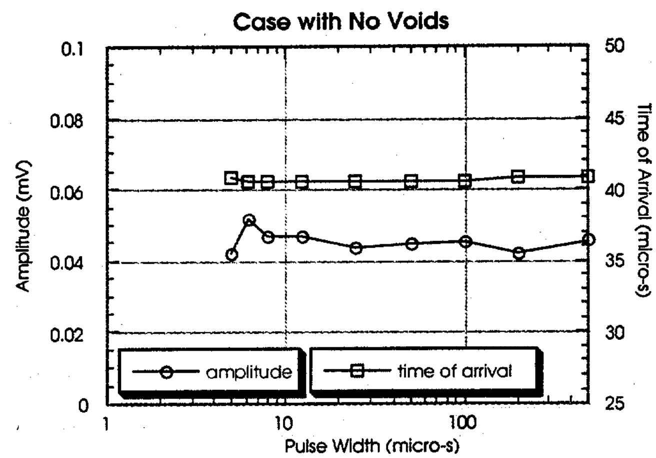

Figure 7 Amplitude of the first wave at the receiver and wave transit time between the transmitter and the receiver as a function of pulse width

RESULTS AND DISCUSSION

First series of experiments for mercury was conducted to obtain baseline data for the system without any voids. Typical data measured for wave transmittance and receiving are shown in Figure 6. A square wave was emitted from the transmitter and the first wave was detected at the receiver about 40 μs later. Wave amplitude of the first wave at the receiver is shown in Figure 7 for pulse width varying from 5 μs to 500 μs. Same figure also shows the time of arrival (that indicates the time taken for the transmitted wave to travel to the receiver). As seen in the figure, wave amplitude at the receiver remains fairly constant indicating that the wave transport characteristic is not a function of pulse width. Sound speeds based on the measured time of arrival are calculated to be 1490~1498 m/s, that is very close to the reported value of 1495 m/s. Small deviation in the sound speeds is thought to be due to impurities contained in the mercury used for the experiments. These measurements also indicate that sound speed measured in our mercury system do not vary much as the pulse width changes.

Second series of experiments was conducted to investigate effects of voids on the sound speed and pressure wave attenuation. Scattering centers were made of thin stainless steel tubes (2.1mm OD & 1.83mm ID) to represent voids in mercury. One end of each tube was sealed to guarantee air inside the tube by preventing any ingress of mercury. Each tube was placed firmly between two plastic holders and dipped into mercury. Because of strong buoyancy, it was necessary to place a heavy piece of metal on top of the tubes.

The number of tubes were arranged in various matrix forms as shown in Figure 8 to represent various void fractions and configurations. Sound speed in mercury with void fractions varying from 0 to 1.2% was measured. Data indicate that the sound speed does not change as void fraction changes in mercury and remains same as the value measured for mercury system with no voids. Wave attenuation with varying pulse width (5μs to 500 μs) is summarized in Figure 9 for the mercury containing various contents of voids. Pulse width is seen again as a non-significant factor affecting the wave behavior. Substantial attenuation is seen as void fraction increases, since the normalized amplitude reduction in the figure comes down from 1 to about 0.25 for the mercury with ~1.2% voids. This indicated ~75% reduction of pressure wave energy for the wave traveling over ~6cm distance of the mercury with ~1.2% voids. This result confirms our earlier observation of substantial attenuation with SCs from the scoping studies. In the scoping studies, the wave attenuation was observed to be more substantial as seen in Figure 2. This is because of substantial cavitation in the mercury in the scoping studies that was induced by continuous high power 20kHz wave generation. This introduced a lot more bubbles or voids into the mercury system. Effective void fraction in the mercury could have been substantial and caused much higher degree of the attenuation in that case.

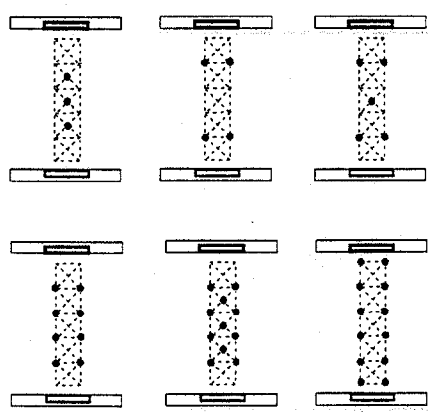

Figure 8 Arrangement of stainless steel tubes representing voids in mercury

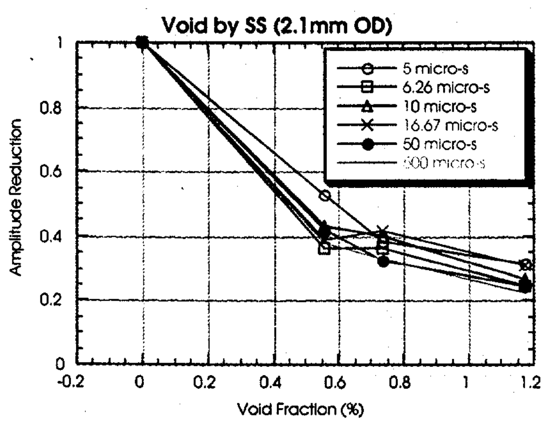

Figure 9 Wave attenuation in mercury with various pulse width as a function of void fractions (SS)

Non-dependency of sound speed with voids in mercury has brought questions on effects of void compressibility. Therefore, the third series of experiments were conducted with flexible plastic tubes (3mm OD & 2.8mm ID) to represent voids in mercury. Void surface represented by plastic surface is very flexible and not rigid as stainless steel tube. When a pressure wave interacts with these SCs, if compressibility was dominant, we expect to observe significant changes in sound speed affected by change in compressibility in mercury-void system. Sound speeds measured for this system are still unchanged from those without voids and with voids by stainless steel tubes. Therefore, issues related to the compressibility change affecting sound speed in mercury have been effectively eliminated. Figure 10 shows the degree of wave attenuation as a function of void fraction for this system. Again, pulse width does not play a significant role in affecting wave attenuation as well as sound speed.

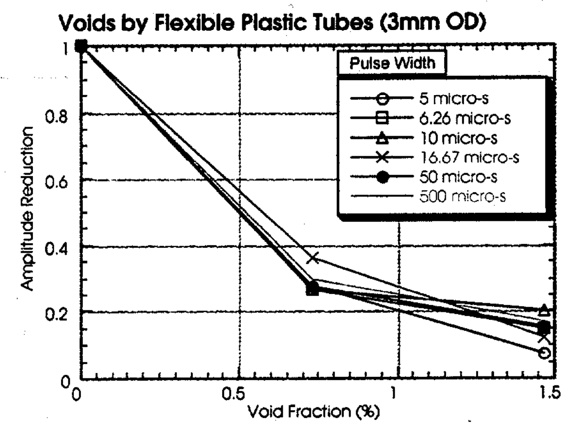

Figure 10 Wave attenuation in mercury as a function of void fractions (Plastic)

The fourth set of experiments was conducted for the mercury system with solid stainless steel rods (1.5mm dia.) as scattering centers instead of hollow stainless steel tubes. As observed before, sound speed remains unchanged from that for the mercury without voids. Figure 11 shows the magnitude of wave attenuation for the pressure wave of 10μs pulse width. Surprisingly, inclusion of solid rods also turns out to give a substantial reduction in pressure amplitude. This observation has naturally brought up strong doubts on how much of the rod surface gets wet by mercury. It has been a well-known fact that mercury is very non-wettable. In this case, the solid rods must have been blanketed with thin layer of air. Consequently, the pressure wave acting on the rods must have seen air voids instead of the rods. This argument becomes true for all other measurements described above with stainless steel tubes and plastic tubes. We can reasonably assume that any voids artificially placed in our mercury system are actually air-voids. Therefore, void fractions for the case with stainless steel tubes as voids were estimated based on outer diameter instead of inner diameter.

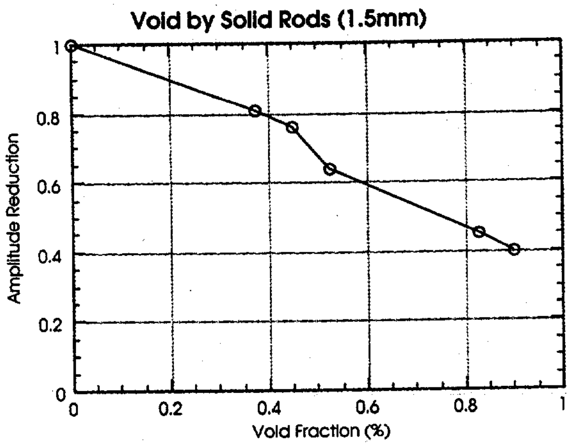

Figure 11 Wave attenuation in mercury as a function of void fractions (Solid Steel Rods)

The fifth series of experiments was focused on homogeneity of void distribution in mercury. Same number of stainless steel tubes was arranged in various patterns, and sound speed and wave attenuation were measured. Figure 12 shows various patterns of eight stainless tubes (1.02% void fraction) arranged between the transmitter and the receiver. Case 1 was the case used to represent voids in the second series of experiments described earlier. As expected, sound speed remains unchanged. The magnitude of the attenuation changes slightly from case to case by as much as 10%; however, it does not seem to be significant from case to case as seen in Figure 13.

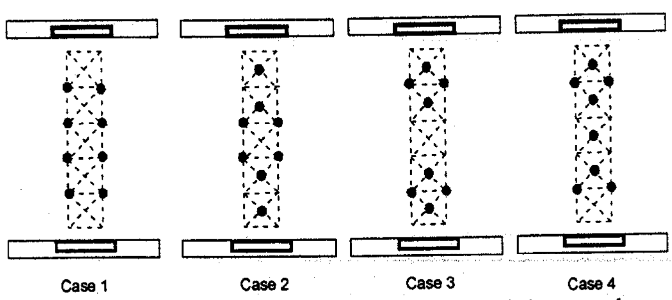

Figure 12 Various arrangement of eight stainless steel tubes

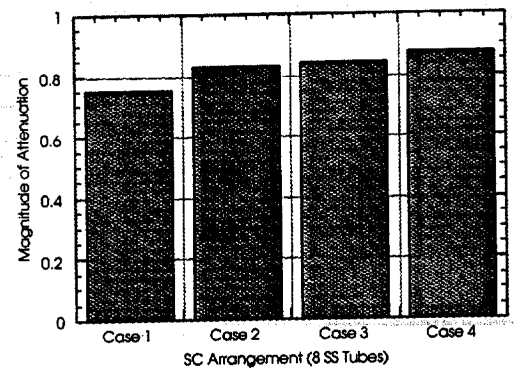

Figure 13 Wave attenuation for various arrangement of stainless steel tubes

SUMMARY

High pressure waves generated due to high energy proton beam in mercury target system of SNS have been design and safety issues possibly threatening integrity of the SNS target structures. A scattering center concept has been developed as a mean to attenuate such high pressure waves and thus to ensure safe operation of the target system. The scoping experimental study indicated that including SCs in a mercury system could be extremely effective in attenuating pressure waves. More extensive experimental studies followed, and revealed that sound speed in mercury does not get changed by inclusion of SCs of various materials. These studies also show that pressure waves could get attenuated to a significant extent with inclusion of SCs in the mercury system.

REFERENCES

1. T.A. Gabriel, et al., "Overview of the SNS Target Station," Proc. of Int. Topical Meeting on Advanced Reactor Safety, ARS'97, Orlando, Florida, 1997.
2. R.P. Taleyarkhan, S.H. Kim, and J.R. Haines, "Results of Thermal Shock Modeling and Analysis for the National Spallation Neutron Source, " Proc. of International Conference on Accelerator Applications, AccApp'97, Albuquerque, NM, Nov. 1997.
3. R.P. Taleyarkhan, and S.H. Kim, "Overcoming Thermal Shock Problems in Liquid Targets," Transaction of the 2000 American Nuclear Society Annual Meeting, pp 25-26, San Diego, California, June 4-8, 2000.
4. S.H. Kim, C.L. Knaff, and R.P. Taleyarkhan, "Experimental Studies on Role of Scattering Centers on Wave Energy Attenuation," Transaction of the 2000 American Nuclear Society Annual Meeting, pp 27-28, San Diego, California, June 4-8, 2000
5. R.P. Taleyarkhan, and S.H. Kim, "Use of Scattering Centers for Overcoming Thermal Shock Problems in Liquid Targets," Proc. of International Conference on Accelerator Applications, AccApp'00, Washington DC, Nov. 2000.