

The Role of Cavitation on Initiating Mercury-Steel Wetting

by

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Prepared for consideration for presentation and publication at the 2001 Annual Conference of the American Nuclear Society, Milwaukee, Wisconsin, June, 2001.

SUMMARY

In accelerator-driven neutron sources such as the Spallation Neutron Source (SNS)' with powers in the 2 MW range (time-averaged), the interaction of the energetic proton beam with the mercury target can lead to very high heating rates in the target. Although the resulting temperature rise is relatively small (a few °C), the rate of temperature rise is enormous (-10^7 °C/s) during the very brief beam pulse ($-0.58 \mu\text{s}$). The resulting thermal-shock induced compression of the mercury leads to the production of large amplitude pressure waves in the mercury that interact with the walls of the mercury target and the bulk flow field. Understanding and predicting propagation of pressure pulses in the target are considered critical for establishing the feasibility of constructing and safely operating such devices. Safety-related operational concerns exist in two main areas, viz., (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 their impact on mercury-steel interfacial phenomena (such as wetting, mass transfer and erosion).

As mentioned previously, it is important to study the impact of volumetric pressure oscillations on the phenomenon of mercury-steel interaction. Computed fluid pressure oscillations in the SNS target system are in the $\pm 15 \text{ MPa}$ range² at mercury-steel surfaces. It has been shown³ that non-degassed mercury over a range of temperatures spanning the expected values in the SNS target will cavitate at only modest rarefaction pressures (close to 0 bar), giving rise to the possibility of jetting-induced loads and possibly improving the wetting between mercury and steel. The likelihood of mercury cavitation in the SNS target makes it important to provide due consideration on some of the materials-related effects this phenomenon may have. Improved contact between mercury and steel under prolonged conditions may also lead to mass-transfer phenomena in which significant steel (target envelope) metal loss may take place.

In order to study the relative effect of cavitation on enhancing wetting of stainless steel (SS) surfaces a simple apparatus type was devised as shown in Figure 1. The apparatus consists of a

Pyrex™ glass cylinder (5.7cm diameter x 11.5cm height) with a cylindrical piezo-ceramic driver attached to the outside of the glass cylinder. Drive electronics consisted of a programmable waveform generator coupled with an amplifier. A pill-microphone attached to the system monitored changes in the wave shape on onset of cavitation and was a good indicator for the onset and intensity of cavitation (which was further corroborated via direct visual evidence and also changes in pressure profile traces when a calibrated pressure transducer was utilized). The application of maximum possible oscillating voltage (about 300V peak-to-peak) to the piezoelectric driver results in an oscillating pressure field with a peak-to-peak fluctuation of about -0.5 MPa in the central region of the mercury. This value was measured via use of a PCB™ calibrated pressure transducer. Although this value is very significantly lower than the expected (~± 15 MPa) pressure fluctuations in the SNS target system, it was enough to permit mercury cavitation to take place. A SS-316 coupon sample (2.5cm x 1.9cm x 0.1cm) was placed midway in the top section of the glass apparatus and held in place with a clip. The lower end of the glass test section was capped off using a plastic disk that acted as a reflecting surface.

Experiments were conducted by dipping the coupon samples in the mercury at room temperature for 24 hours without cavitation in the mercury. These samples, when pulled out displayed no evidence of wetting. Upon introduction of cavitation for 24 hours and 48 hours at -20 kHz drive frequency (the first resonant mode of the system), the coupon samples upon withdrawal displayed clear wetting of mercury. Mercury covered virtually the entire surface and clung to it. Conclusive mechanical wetting occurred between mercury and steel. The mercury layers were wiped off and taken for metallographic examination. Each of the specimens were noted to have lost about 10 mg in the short term exposure at room temperature. Interestingly, the largest weight loss in an operating loop (without cavitation) for a similar specimen was about 16 mg (in 5000 hours at 300°C in mercury flowing at 1 m/min). Ordinarily, in an operating mercury loop at lower temperatures of about 100°C insignificant weight loss is experienced. Clearly, something “different” was happening in the tests with cavitation. This could be physical erosion from cavitation, or there could be some mercury interaction aspects in combination with erosion.

Scanning electron microscopy (SEM) was next attempted on two coupons - one "unexposed" and another exposed 24 hours in mercury under cavitation conditions. The exposed surface was noted to have become very rough and developed lots of surface relief. It contained very tiny beads of mercury in some of the deepest/roughest pits on the surface, but there was no evidence of chemical "wetting". Microprobe chemical analysis indicated only tiny discreet areas of mercury - no "amalgam films" or such indicators. Some photos were developed to compare both the relatively smooth unexposed surface and the roughened surface after exposure to the mercury. Stereo (3D) imaging was also attempted. The photos suggest that the typical surface profile on the unexposed specimen is very even and varies only +/- 0.5 μm or so in most areas. The specimen exposed to cavitation has 10~12 μm valleys (measured from the remaining surface position) all over with many small areas much deeper than that. Furthermore, it is to be noted that the original surface has been removed, so the 10~12 μm valleys are actually somewhat deeper (depending on how deep the general thickness loss is). Microprobe analysis has also been performed on cross sections of the surface of the specimen exposed for 24 hours. After only modest cleaning efforts, there appeared no trace of residual mercury on/in the surface profile and there was no composition gradient in the 316L akin to the Ni and Cr depletion seen in the experiments with flowing mercury at 300 °C. This suggested that, in the tests with the Figure 1 apparatus (including cavitation), despite mechanical wetting, the mercury did not chemically wet or interact with the 316L in any substantial way; the temperature at -24 °C was probably just too low. However, erosion was evidently very significant at low temperatures. The presentation will discuss salient implications on liquid target operation, additional experiment configurations for wetting and visual data for specimen states with and without cavitation.

References

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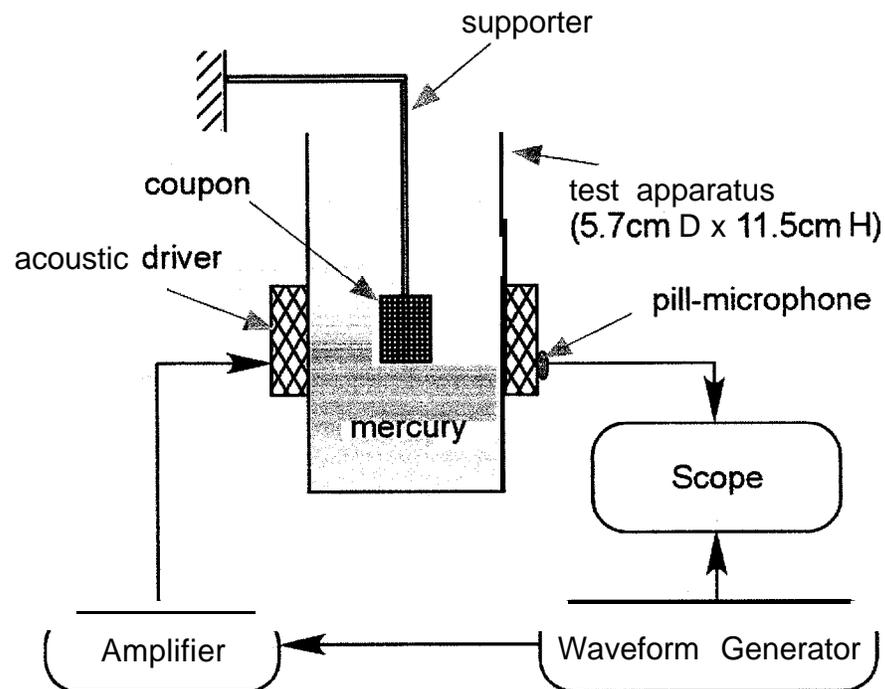


Figure 1. Test Section Geometry (with stainless steel coupon sample)