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RADIATION INDUCED CAVITATION: A POSSIBLE PHENOMENON IN LIQUID TARGETS?

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ABSTRACT

The proposed design of a new, short-pulse spallation neutron source includes a liquid mercury target irradiated with a 1 GeV proton beam. This paper explores the possibility that cavitation bubbles may be formed in the mercury and briefly discusses some design features that could avoid harmful effects should cavitation take place.

I. INTRODUCTION

Under normal conditions, most liquids have rather well defined freezing and boiling points. However, it is well known that clean liquids, with reasonable care, can be supercooled or superheated, finally changing phase only considerably below the freezing or above the boiling point. An everyday example of superheating is a clean glass of previously boiled, clean water reheated in a microwave oven. But I do not recommend that experiment because the final boiling event is violent, even explosive.

To any physicist more than about 50-years old, a familiar example of superheating is the bubble chamber. In the bubble chamber, invented by Donald Glaser in 1952,[1] a volume of appropriate liquid is superheated at a constant temperature by suddenly lowering the pressure from above the saturation pressure to below it. After the depressurization, there is an appreciable period before general boiling creates enough vapor bubbles to repressurize the system. During this period, an energetic particle (e.g., a high energy proton or electron) passing through the liquid leaves behind it a track of small, but growing bubbles (Figure 1). As the particle is slowing down in the liquid, it transfers kinetic energy (i.e., it heats) to the liquid molecules. If sufficient heat is deposited in a small enough volume, the liquid will vaporize locally, forming a tiny bubble, –100 Å to 1000 Å. If the liquid is above its boiling point (i.e., if it is superheated) this tiny bubble, or nucleation center, can grow by evaporation of the liquid. From stereo photographs of the bubbles, the track of the particle and of its decay or reaction products can be reconstructed. This is the classic bubble chamber, which dominated high-energy physics experiments for more than a decade. It earned Glaser the Nobel prize for physics in 1962.[2]

It is less well known that liquids can be subjected to a negative pressure, or tensile stress. An everyday example of this is a tree. At the base of a tree, the sap in its capillaries is at approximately atmospheric pressure: a cut does not cause sap to spurt out or air to be sucked in. Gravity causes the pressure in any vertical column of liquid with approximately the density of water to fall by 1 atm for every 10 m or so of height. Therefore, the sap above a height of about 34 ft is at a negative pressure. The foregoing statement is usually met with intuitive disbelief, but there is a simple demonstration.[3] From the ground, a marksman with a rifle shoots through a twig near the top of a tall tree. The severed twig falls to the ground and, upon examination, it is found that the sap has retreated from the cut some distance into the capillaries. The twig is now placed into a pressure chamber with the cut end protruding, through a cuff seal, into the air. The pressure in the chamber is increased, squeezing the capillaries, and sap is forced out of the twig. The gauge pressure in the chamber needed to bring the sap surface level with the cut end is equal to the negative pressure that was in the liquid-filled capillaries of the twig at the instant it was severed.

There are several straightforward methods of subjecting a liquid to negative pressure. One is basically the same as the tree example: a long enough barometer with a low enough pressure at its base[4] (Figure 2).

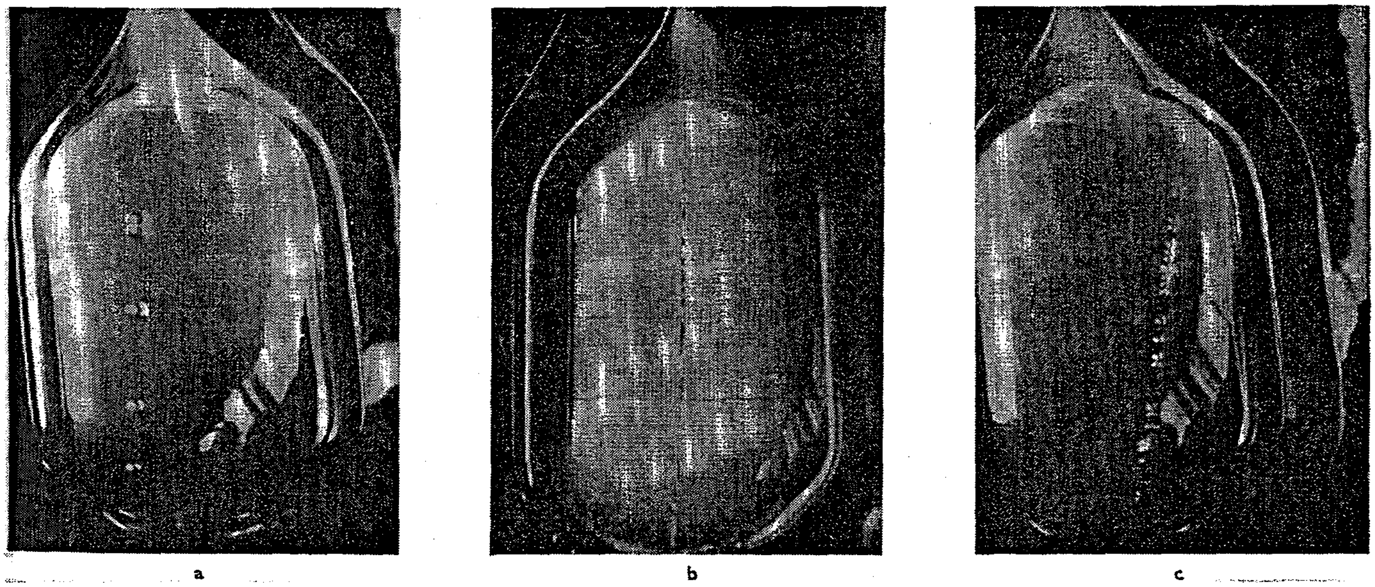

Fig. 1. Penetrating cosmic radiation tracks in Glaser's diethyl ether bubble chamber. Random expansion and counter-controlled flash-lamps. (a) 60 μsec flash delay, 20 μsec flash duration, 139°C, (b) 10 μsec flash delay, 20 μsec flash duration, 140°C, (c) 10 μsec flash delay, 5 μsec flash duration, 141°C. The track in (c) is deflected about 2° in the middle of the chamber. (D. A. Glaser, Handbuch der Physik, Bd. 45, Berlin 1958).

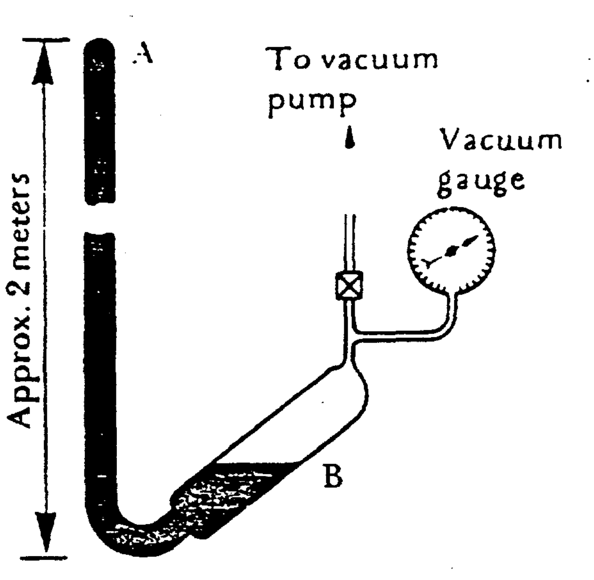

Fig. 2. Tension manometer, T. J. Hayward.[13]

Another is Berthelot's method,[5] in which an evacuated container (usually of glass) is almost completely filled with liquid and sealed. The apparatus is then carefully heated, and the liquid expands more than the container, eventually filling it completely. Upon cooling, the liquid would like to contract more than the container, but if the liquid and the surfaces are clean and free from nucleation centers, the liquid "adheres" to the surface and is thereby forced to occupy a larger volume than it wishes, putting it under a tensile stress. Eventually, if cooled far enough, the liquid "breaks," with a distinct click, forming a bubble. The process can be repeated by raising the temperature again. A more sophisticated version of this apparatus, created by Meyer,[6] actually incorporates a Bourdon gauge into the container, allowing the negative pressure to be observed and measured in a very direct way (Figure 3). The present author has demonstrated that bubbles can be nucleated by fast neutrons in a Berthelot-type apparatus.

A third method is also related to the tree example. It appears in at least three basic versions [7,8,9] but is usually called the Briggs' method. The version shown in Figure 4 was first used by Hahn to demonstrate bubble nucleation in a negative pressure liquid by atomic particles. In Hahn's apparatus an open-ended tube with bent back ends, almost filled with liquid, is rotated about a vertical axis. The ends are open to atmospheric pressure, so the apparatus is basically a double-limbed, or inverted U-tube, barometer with the effect of gravity being replaced by the centrifugal acceleration of the rotating tube, which, at high rotational speeds, can produce very steep pressure gradients. With this apparatus, negative pressures of 100 atms or more can easily be produced and, in suitable liquids under suitable conditions, sustained.

A fourth approach is to apply intense acoustic, or other, pressure waves. For example, an acoustic wave with a pressure amplitude of 10 bars in a liquid at a mean pressure of 1 bar (atmospheric) will put that liquid under negative

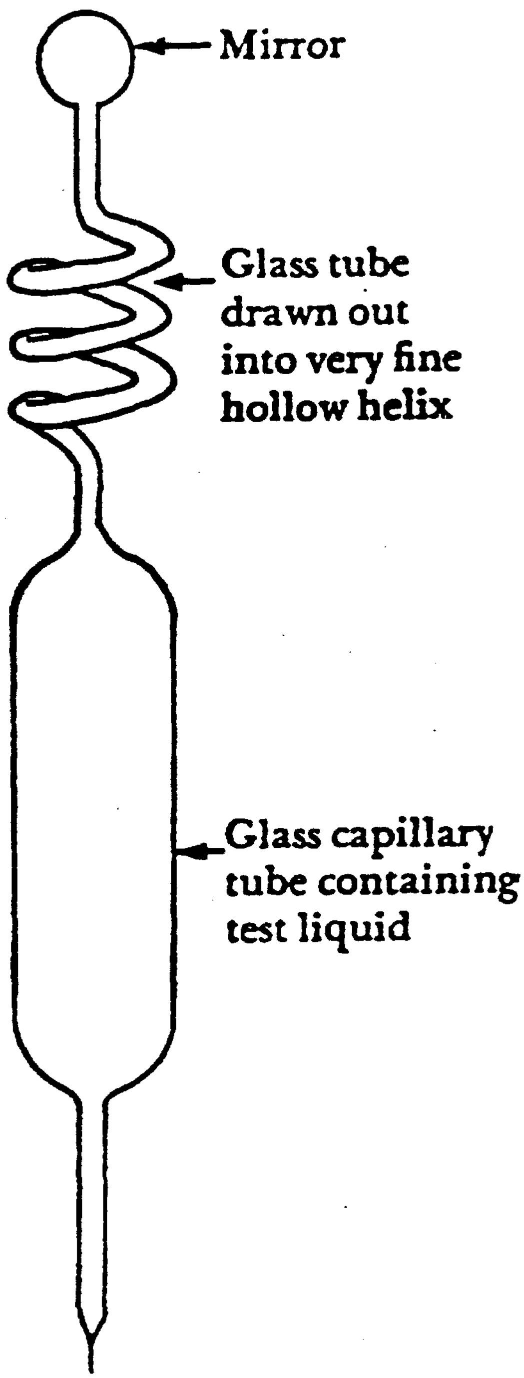

Fig. 3. Negative pressures—Meyer's more sophisticated form of Berthelot's Method, T. J. Hayward.[13]

pressure for almost the whole of the negative going part of the pressure cycle. Bubble nucleation by radiation has been demonstrated in these circumstances also.[10] It is not necessary to have a continuous pressure variation, as in a sound wave: a single pressure pulse propagating through a liquid will reflect from a low-density boundary (e.g., air) with a change of phase, retraversing the liquid as a rarefaction pulse, which can lead to cavitation bubbles (cavitation is the name usually given to the formation of bubbles by reducing the pressure on a liquid that is below its normal boiling point). The subsequent collapse of these bubbles, when the pressure rises again, can be very violent, and can crush or erode nearby solid objects. The lithotripter[11] is designed expressly to focus a pressure wave, from a transducer outside the body, onto kidney stones: the pressure pulse reflected from the stone creates a large cavitation bubble whose subsequent collapse disintegrates the stone without invasive surgery.

Figure 5 is a dramatic example of cavitation erosion. In this, as in most cases, radiation was not involved in the formation of the cavitation bubbles: unless a liquid has been carefully purified and degassed, there are usually enough particles or gas bubbles to act as nucleation centers and form bubbles as soon as even a slightly negative pressure is applied.

For a further discussion of negative pressures, and descriptions of still other means to generate negative pressures, including hydrodynamic effects around objects moving through liquids, Hayward's article[12] is highly recommended.

II. CAVITATION IN A LIQUID METAL SPALLATION TARGET?

In a spallation source, neutrons are produced when a high energy beam of, usually, protons strikes a target material. Typically, the proton energy is ~1 Gev, and such a proton releases ~30 neutrons upon its interaction with a high atomic number nucleus in the target material. For a short pulse spallation source currently being designed,[13] there may be 60 pulses per second, each lasting less than 1 μs and carrying 17 kJ. Liquid mercury is the target material, and most of the proton pulse energy is absorbed in a relatively small volume, ~1 L, of the target. This causes very rapid local heating and thermal expansion, which generates a pressure wave traveling outwards from the heated region. Upon reaching the walls of the mercury container, the pressure wave will be reflected with a 180° change of phase, unless successful measures are taken to match the acoustic impedances of the wall and the mercury appropriately. Calculations indicate[14] that the amplitude of this rarefaction wave may be ~350–400 bars in the bulk of the mercury and 100 bars even near the container walls.

Unless the mercury is kept under an equal or higher positive static pressure, there will be short periods of negative pressure.

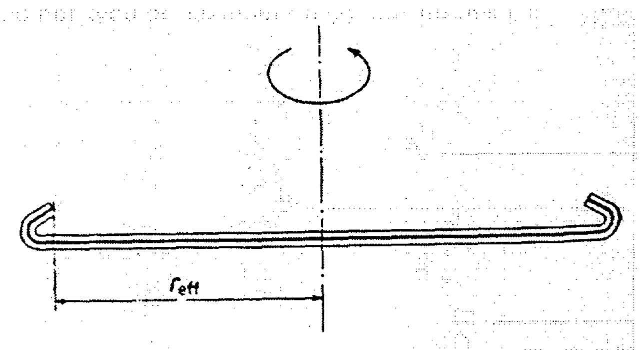

Fig. 4. Rotating pyrex glass capillary tube, Hahn.[9]

In that case, unless the mercury was extremely carefully purified and degassed, cavitation bubbles would be formed: the highest negative pressure sustained by mercury in Briggs' experiments, after extreme efforts to remove nucleation centers, was 425 bars[15] at 28°C: presumably the threshold would be even lower at the temperature, >150°C, of the spallation source target. And even if it was free of nucleation centers, energetic recoiling nuclei or decay products from the spallation reactions could cause bubble nucleation,[16] as in some of the experiments described above.

III. SHOULD WE CARE?

Cavitation in the bulk of the mercury target is probably not a serious problem. Indeed, one way of reducing the intensity of the pressure wave, in order to mitigate the stress loading on the container, is to fill the mercury with bubbles. Only if the number and size of the cavitation bubbles remaining in the region receiving the proton pulse when the next pulse arrives were large enough to reduce the average density of that region significantly would there be a significant impact on the neutron production.

Cavitation on the surface of structures in or around the mercury may be a more serious event: as Figure 5 shows, serious mechanical damage could ensue. Fortunately, even if planned experiments at Brookhaven's Alternating Gradient Synchrotron were to show that such damage might arise, there are design choices that could reduce or eliminate the effects. Holmer et al[17] showed that the fragmentation action of the lithotripter was considerably reduced by covering the surface of a test stone with a resilient film of silicone in their case. In addition, the acoustic impedance mismatch between the mercury and its container walls, and therefore the reflection of the pressure wave, could be reduced by choosing the material and thickness of the wall structure appropriately. Finally, the amplitude of the pressure wave reaching the wall could be reduced by placing bubbles or objects such as resilient films or hollow spheres between the origin of the pressure wave and the structural components.

Fig. 5. Example of severe cavitation damage to an agricultural pump impeller.

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