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Discussion session summary: cavitation erosion

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The present account gives a brief summary on a discussion session in which the present state of knowledge and activities relating to corrosion and erosion in heavy liquid metal targets was reviewed and future plans were discussed. Since the emphasis of the conference was on short pulsed spallation sources, work done in conjunction with other spallation targets, such as accelerator driven systems (ADS) using PbBi as target material, played only a minor role, although the scope of the work done world-wide on this topic exceeds that on pulsed mercury targets significantly.

1. Liquid metal corrosion

Corrosion in liquid metal loops is generally viewed as a result of material transport: constituents of the wall material are dissolved in the liquid metal at locations of high temperature and segregate to the walls at positions where the fluid temperature and hence the solubility for foreign atoms is lowest. The best way to minimize this effect is usually considered to be an intact oxide, carbide or nitride layer on the surface that prevents direct contact between the solid and the liquid metal. The problem is most extensively studied for PbBi as target material, because here severe problems may be encountered at elevated temperatures (above 400–500 °C). A solution identified in this case is careful control of the oxygen activity in the liquid metal with the aim to keep it at a level sufficient to maintain the oxide layer on the wall surfaces but not enough to support oxidation of the lead and bismuth itself. The necessary conditions are now well understood and probes have recently been developed that allow to monitor the oxygen content in PbBi even at temperatures below 400 °C, which used to be the lower temperature limit for this technology until recently. This is the outcome of a large R&D effort carried out in the context of ADS and, as a prototype, the MEGAPIE project. By comparison, research on corrosion by mercury as a target material is much more limited. This is mainly because results obtained so far seem to indicate that there is not a problem at the temperature and pressure regime in question for the next generation pulsed neutron sources. It is worth noting, however, that oxygen contained in the cover gas of a mercury loop may easily be transported to the interior of the loop and may lead to the formation of mercury oxide crystals, which can block narrow passages or affect heat transfer to and from surfaces. Since in a spallation target there will be free hydrogen produced, which one might wish to oxidize for trapping in a filter, the question of oxygen content and oxygen handling in a mercury target may still be of importance but is not a pressing issue at the moment for the ongoing project (Spallation Neutron Source (SNS), Japanese Spallation Neutron Source (JSNS) and European Spallation Source (ESS)).

2. Cavitation erosion

The problem that needs to be and is being studied with urgency for these projects results from the pulsed power input into their targets and is related to the generation of pressure waves. Such pressure waves are the result of the fact that the liquid cannot relax fast enough to accommodate the thermal expansion of the volume heated by the intense proton pulse during a very short time. This leads to the build up of pressure that travels outward to the walls as a wave front and causes elastic strain in the walls. It is then reflected back and the rarefaction phase of the wave produces negative pressure that cannot be sustained by the liquid, which responds by the formation of voids (cavities). So far, little is known on the details of the events going on near the wall. Attempts to obtain a clearer picture through the measurement of time dependent surface strains on

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the containers of test targets and to compare them to the results of theoretical calculations have not been fully successful, although different CFD codes yielded very similar results. This shows that the response of the system to pressure impacts is more complicated than the way it is dealt with in the codes.

The lack of understanding is particularly obvious for the phenomenon called 'pitting, which is observed in the context of such experiments, and which is a particular kind of damage inflicted on parts of the surface of the walls in contact with the liquid metal. Such pitting was first observed in Split Hopkinson Bar Tests (SHBT) carried out by the JAERI team about two years ago, but has now been produced also in pulsed proton beam tests at the WNR facility in Los Alamos. The basic phenomenon is the same in both cases: depressions (indentations with no material removed) and craters (little features resulting from very localized removal of material) are observed in certain regions of the walls. In the WNR beam tests, these regions were mainly the flat front and rear flanges of the cylindrical targets, while no effects were observed on flat specimens arranged along the walls of the cylinders. Another puzzling fact is that the most intense damage in these tests was not found at the location where beam intensity was highest (as inferred from activation measurements), but symmetrically displaced from it with respect to the symmetry axis of the target. Both of these observations lend arguments to the speculation that the effect is not a direct one that occurs as an immediate consequence of the power input (heating) but at a later stage when a complicated pattern of wave interference develops in the target. It may be assumed that the cause of the pitting is the collapse of small bubbles in the immediate vicinity of the walls, which are generated when the local pressure in the liquid tries to go below a certain negative value, because the ability of the liquid to sustain tension is much smaller than that of solids.

> Hence, geometry may be expected to play an important role in the cavitation erosion observed, and in this respect the targets investigated so far were in no way prototypic for either one of the targets planned for the next generation spallation sources. This is also true for the fact that the mercury was not flowing in any of the tests, although no indications exist so far that flow might be an important factor.

It should also be mentioned that pitting was particularly severe on the walls enclosing a thin volume of mercury meant to simulate the cooling channel of the SNS beam entrance region of the target. Like the outer wall, the side of the separating wall facing the small volume was heavily damaged while the side facing the larger body of the target showed almost no damage. This supports the view that *geometry and confinement* play an important role.

Surfaces that had received a hardening treatment ('Kolsterizing') before irradiation also showed a tendency to be less damaged than the annealed material.

> Although it remains questionable, whether surface hardening can be a sustainable solution for a wall on which heavy radiation damage will be inflicted, it seems to be clear that there is an effect of the hardness of the material on its susceptibility to cavitation damage.

The question, whether there is a quantity ('figure of merit') that correlates different materials or different conditions with respect to pitting by mercury could not be resolved. Hardness alone, or hardness in conjunction with Young's modulus might play a role, but data are way too sparse and inconclusive to allow such correlations to be established. It also seems difficult to transfer to mercury rules established for water. This may have to do with the differences between a molecular liquid and a liquid metal.

There is hope for the understanding of the phenomena to improve as the experimental data base on cavitation erosion in mercury can be expected to grow rapidly in the near future with a number of tests planned or in preparation at the time of the Conference. While the parameter space that ultimately needs to be explored is rather large, the most pressing questions identified are:

- The extrapolability of the damage observed at no more than 200 pulses to the anticipated minimum of 200 million pulses a target would experience during its life time, if radiation damage alone was the limiting factor. In order to investigate this, out of beam tests with different methods to produce damage are under preparation at all interested laboratories.
- In view of the reduced pitting on hardened surfaces, is there a threshold in terms of number of pressure beyond which the effect takes off rapidly?
- Are the different characteristics of features observed (depressions, small and large craters) all the results of single events or is there repetitive bubble formation at the same spot, indicating stable nucleation centers for cavities?
- The effect of flow along the walls. Fluid flowing along the wall might reduce the number of nucleation centers, if such centers play a role in the process.
- The effect of wetting. Again the number and effectiveness of cavity nucleation centers on the walls might depend on the wetting conditions, i.e. on the questions whether there is a velocity gradient near the wall or whether the liquid is simply slipping across the wall.

- The dependency of the damage on the frequency of excitation. So far, all experiments were carried out at very low repetition rates of no more than 0.3 pulses/s. This probably implies that all bubbles generated in one pulse have collapsed before the next pulse occurs. This may not be true at 50 or 60 Hz as foreseen for the real targets and the remaining bubbles may have a damping effect on the subsequent pressure pulse.
- The effect of artificially introduced gas bubbles on the development of a pressure wave. Speculations on such an influence date back to the days when mercury targets were first proposed for pulsed sources and have recently been substantiated by more detailed calculations taking into account the size dependent resonant oscillatory behavior of the bubbles. From these calculations it is expected that a volume fraction of 1% of bubbles of about 40 μm in size should reduce the pressure build up by nearly three orders of magnitude. Intense efforts to develop suitable methods to generate such bubbles are led by the ESS project in collaboration with SNS and JSNS.

Some of these aspects will be addressed in a series of experiments carried out in late June 2002 at WNR, but possibilities to investigate all of the above questions are limited there. Nevertheless, there is hope that, together with off-beam tests under preparation at all interested laboratories, the results will be sufficient to support the SNS decision of whether or not to stay with the liquid metal target for the commissioning phase of the project. More long term future efforts to develop very high power liquid metal targets, which are clearly of interest beyond the current projects, will need to rely on as prototypical test conditions as possible. In parallel development of codes that incorporate more detail of the behavior of the systems under the conditions in question is ongoing but will need more input also. The laboratories now developing the next generation pulsed sources have started to explore such options together with other groups that work on similar problems.