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Materials research and development for the spallation neutron source mercury target ☆

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Abstract

In the Spallation Neutron Source target, the structural material will be exposed to intense pulsed fluxes of high-energy protons and neutrons, which produce radiation damage. These pulsed fluxes also lead to pressure pulses created by beam heating. In turn, the pressure pulses give rise to fluctuating stresses in the 316 LN austenitic stainless steel target vessel, and to cavitation in the liquid mercury spallation target. Corrosion reactions and related changes in mechanical properties also may occur through contact with flowing mercury. We describe the materials research and development program for the spallation target. The program covers the areas of cavitation erosion, radiation effects, and compatibility. Cavitation erosion work includes pressure wave tests at the LANSCE proton accelerator, as well as laboratory tests that simulate aspects of the actual in-beam exposures. Materials irradiations are being carried out in spallation environments at high-energy and high-power proton accelerators. Other experiments are conducted at irradiation facilities that simulate aspects of spallation conditions. Extensive radiation damage and transmutation calculations supplement these experiments. Compatibility work includes both thermal convection and pumped flow loop tests to examine temperature gradient mass transfer, as well as fatigue and tensile tests in contact with Hg. Based on the information developed for radiation effects and compatibility with mercury, our analysis indicates that the target will meet its intended service requirements. In the past year and one half the new issue of cavitation erosion has been included in the program. Both in-beam and laboratory experiments indicate that cavitation erosion may occur in the target. The highest priority activity is now to determine whether cavitation erosion will limit target lifetime to a level below the lifetime limit set by radiation effects.

1. Introduction

The Spallation Neutron Source (SNS) is an accelerator-based neutron scattering facility that will provide intense pulsed neutron beams that are created by irradiating a mercury target with 1 GeV protons. The overall design and progress of the facility are described in a companion paper in these proceedings [1] and in a related presentation [2]. In total the design, construction and R&D for the facility are 45% complete at the present time, with the R&D itself being about 90% complete. The timing of the present workshop therefore offers a propitious opportunity to give an overview and perspective on the materials portion of that effort.

Our previous reviews document the progress of the materials work [3–6]. In Ref. [6] other areas of R&D including thermal performance, particle transport and remote handling were mentioned. Thermal performance research, consisting of thermal hydraulics and thermal shock testing and analyses, was described in some detail because it and the materials work strongly affect each other. Again in the present manuscript it will become clear that thermal shock and materials issues are tied together. It is interesting to gauge the rapid progress or research and development by comparing Ref. [3], of

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about five years ago, with Ref. [6], of about two years ago. The materials program currently includes several significant activities that were not described in Ref. [6], because they were either non-existent or not pursued at significant levels. Similarly, Ref. [6] contains descriptions of work not at significant levels at the publication dates of Refs. [3–5]. The present paper pursues three objectives: (1) To summarize progress in the intervening period on continuing R&D for some of the tasks described previously; (2) To summarize progress in major new work that was initiated in 2001, after the prior meeting in this series; and (3) To give a perspective that benefits from the present vantage point of a longer overall time span since the materials R&D program was launched in 1995.

2. Background

The main work in the materials R&D program covers the mercury target container module. This component has to bear the greatest loads in terms of radiation dose, stress and contact with high velocity flowing mercury. Although the work emphasizes the target, other areas that have received significant attention are materials issues for the moderator containers, for the inner plug region and for process systems. The first two of these components will receive substantial radiation doses because they are in close proximity to the target module, while the third area presents a range of more or less conventional water corrosion issues. Fig. 1 shows the target module, moderators and reflector region of the facility.

A description of the target container module, a most important component of the SNS, is given in Ref. [6]. Three materials issues are currently being addressed related this component. These are cavitation erosion, radiation effects and compatibility with mercury. For the target module, activities on radiation effects and compatibility with mercury were initiated at the inception of the R&D program in 1995, and progress in these areas is summarized in Refs. [3–6]. After extensive testing and analyses we have a firm technical basis to expect that the selected material, type 316 LN stainless steel, will fulfill its intended service requirements with respect to radiation effects and compatibility. In turn, the setting of these requirements themselves was influenced by the R&D program, in a systematic process of matching needs and performance capabilities. Unlike the situation in the above two areas, however, almost all work on cavitation erosion has been carried out since the last International Workshop on Spallation Materials Technology in October of 2000 [7]. Most of this work consists of intensive activities in Japan, Germany and the USA that are highly collaborative in nature, and most of the results of this work to date are being published for the first time in the present proceedings. Prior to the current intensive efforts, some exploratory work on cavitation erosion specific to the use of a liquid mercury target had been done at ORNL about four years ago [8–10].

For workers already familiar with materials issues like radiation damage and corrosion in fission and fusion reactor technologies, the need for the SNS materials R&D program can be motivated by drawing several comparisons. (1) Typically fission reactors are steady-state devices, where the power level and hence displacement damage rate usually exhibit only gradual variations with time. The SNS will be pulsed, with a proton beam pulse length of $\sim$0.7 μs and a repetition rate of 60 Hz. Thus while the time averaged damage rate in the SNS target container will be similar to that in a high flux fission reactor core or in a magnetically confined fusion power reactor first wall, the instantaneous damage rate during a proton pulse will be about four orders of magnitude higher (10^{-2} vs. 10^{-6} dpa/s). (2) The pulsing also will create pressure waves by rapid heating in the mercury, which in turn will both cause stress transients in the target container and induce cavitation in the mercury. (3) In fission reactors almost all neutrons have energies less than 10 MeV and in fusion reactors operating on a D–T cycle all neutrons have energies below 14.1 MeV. By contrast, in the SNS the protons impinging on the target have energies of 1 GeV. The neutrons created in the target by reactions of mercury with these protons have energies ranging up to the proton energy, although the neutron spectrum can be viewed qualitatively as a hardened version of a fission spectrum with a tail extending up to the proton energy. (4) These high particle energies result in transmutation rates of He and H per unit displacement damage that are two to three orders of magnitude higher than in a typical fission reactor core. They are also up to an order of magnitude higher than in the first wall of a fusion reactor. In addition, a wide range of other transmutation products is produced at higher rates than in fission reactors. (5) In most fission reactors and in contemplated fusion reactor designs the structural materials are in contact with water, gas or alkali liquid metals. In the SNS target the contact medium will be liquid mercury. Succinctly stated, we do not have knowledge from previous work in fission or fusion reactor technology that is directly applicable to SNS conditions.

The SNS R&D program was created to supply the technical information required to support the engineering design of the facility. The considerations above indicate the range of issues being confronted in assessing the expected performance of materials in the target module. Unfortunately, there is not a currently available prototypic test environment for the target. In the absence of such an ideal test bed, radiation damage calculations and a wide variety of experiments using many

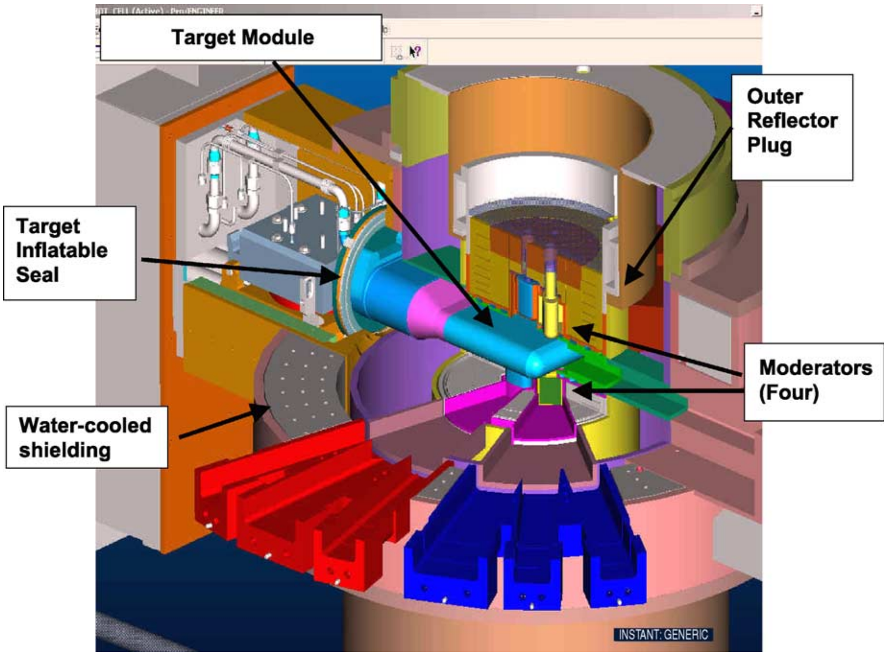

Fig. 1. The target region showing the mercury-containing target module, the four moderators, the reflector, and shielding.

available capabilities in irradiation and non-irradiation environments are being employed to piece together the information needed. A summary of these efforts is given in Table 1. It is a substantially updated version of a table shown in Ref. [6]. Nine attributes that may be considered potentially important to material performance are listed across the top. In the left hand column are 12 types of experiments to determine materials behavior, with the governing conditions of SNS given in the top row. A material in the SNS target module will by definition experience all nine of the parameters in the ranges of interest. The experiments represented in the rows below the SNS row each address some of these parameters, but none addresses all. The five rows below the SNS row are irradiation experiments, but typically do not address mercury issues. The next four rows are compatibility experiments, and the last three rows address cavitation erosion. None of these latter seven types of experiments addresses irradiation considerations. While no substitute for a prototypic experiment that addresses all conditions

Table 1
Summary of attributes of the SNS target environment and R&D efforts designed to address materials issues related to this environment

Experiments	E	dpa	He/dpa	H/dpa	Hg flow	T (°C)	σ	Cycles	Cavitation
SNS	$\leqslant$ GeV	$\geqslant 10^{a}$	$\geqslant 50$	$\geqslant 500$	High	$\leqslant 200$	High	$\leqslant 10^9$	Yes
3-beams	~MeV	$\geqslant 10$	$\geqslant 50$	$\geqslant 500$					
p into liq.	~MeV	$\leqslant 5$			High	$\leqslant 200$	High		
LANSCE	<GeV	$\geqslant 10$	$\geqslant 50$	$\geqslant 500$	(H_2O)	$\leqslant 200$			
SINQ	<GeV	$\geqslant 10$	$\geqslant 50$	$\geqslant 500$	(H_2O)				
HFIR	~MeV	$\geqslant 10$	$\leqslant 50$	$\leqslant 10$	(H_2O)				
TC loop					Low	$\leqslant 300$			
P loop					High	$\leqslant 300$			
Tensile					Static	~25	High		
Fatigue					Static	25	High	$\leqslant 10^9$	
WNR					Static	25	High	$\leqslant 200$	Yes
Vibratory horn					Static	25	High	$\leqslant 10^9$	Yes
Impact					Static	25	High	$\sim 10^6$	Yes

In the columns labeled He/dpa and H/dpa the gases are expressed as atomic parts per million (appm).
[a] First target to be removed for examination at 5 dpa.

simultaneously, these experiments allow us to cover all the issues separately or together in some measure.

3. Summary of observations and results

3.1. Cavitation erosion

We had been investigating thermal shock from the aspect of sudden stress loads imposed on the mercury target container via pressure waves created in the mercury. The pressure waves are caused by sudden heating resulting in rapid thermal expansion of the mercury. Both calculations and experiments were carried out to investigate this effect. The calculations predicted relatively large pressure waves and consequently large strains in the container. In pulsed proton beam tests at the LANSCE weapons neutron research facility (WNR), large strains were measured on the surfaces of mercury containers sized to give similar beam-deposited energy density to the SNS target. The magnitudes of the strains, but not their frequency response, were well predicted by the calculations [11].

In the latter part of 2000 our attention shifted to another effect caused by the beam-induced pressure pulses: that cavitation could occur in the mercury and might lead to cavitation erosion of the container. Cavitation erosion stems from the thermal shock produced by the high intensity proton beam pulse impinging on the mercury. When the pulses of proton energy are absorbed in the mercury volume, thermal expansion following the subsequent rapid heating produces pressure waves. These pressure waves propagate at the speed of sound to the vessel walls and are followed by rarefactions. In these regions of tensile stress the liquid loses cohesion and cavitates. Although cavitation bubbles may form throughout the mercury volume, it is those near the container walls that can cause erosion. Collapse near the container wall can give rise to high velocity liquid jets and shock waves. These jets and shock waves may erode the surface. The high intensity of current work on cavitation erosion, also called pitting because of the appearance of the eroded surfaces, was triggered by a discovery of a team of Japanese researchers in the latter part of 2000 [12]. These workers had been carrying out tests to measure wave propagation characteristics in a confined mercury volume subjected to pressure pulses induced by imparting a mechanical impulse to a piston. Their Split Hopkinson Pressure Bar apparatus was disassembled after testing and the stainless steel surfaces examined. Pits were found on surfaces in contact with mercury. Since the pressure pulses in those tests were of similar magnitude to those predicted for the SNS target, research was quickly started at ORNL to determine as closely as possible whether pitting would occur in the actual application. In particular, since pitting was observed in the Japanese tests after only a few pressure pulses, whereas more than 5×10^6 beam-induced pulses will occur per day in SNS operation, the concern was with the possibility of wholesale erosion of the target container material.

A detailed background and numerous recent experimental results supporting the summary of the above paragraph are available in papers of the present proceedings [13–18]. Current research at ORNL can be summarized in terms of three types of experiments: (1) accelerator-based experiments using the pulsed proton beam of the LANSCE WNR to create pressure waves of similar magnitude and origin to those expected in SNS; (2) vibratory horn experiments that produce high frequency low amplitude pressure waves; (3) drop weight experiments that produce pressure waves of the desired magnitude by gravity driven mechanical impulse. Collaborations are underway with Japanese researchers who have developed an electromagnetically driven diaphragm device that is also capable of producing the desired amplitude pressure waves. A variety of other apparatus are also being explored for near term application.

Results of the pulsed proton beam tests in WNR are reported in detail in these proceedings [14,15] and in a recent white paper [19]. Up to the dates of the present workshop more than 100 specimen surfaces had been examined for pitting, comprising a variety of materials and thermomechanical processing routes. Fig. 2 is a graphic illustration of the nature of the pitting issue. The left hand panel is a SEM micrograph showing the distribution of pits over an area of roughly 10 mm^2. The right hand panel is a SEM micrograph showing a single pit at greater magnification. Details suggest that the material has suffered impact fracture, both by the appearance of the pit itself and by the presence of nearby deformation bands.

Another type of test in which significant amounts of cavitation erosion data have been accumulated utilizes a vibratory horn apparatus. Evaluation of materials for resistance to cavitation erosion is often carried out using a vibratory horn. There is an ASTM standard [20] that guides the performance of such tests in water and the evaluation of results. This method has been adapted to our needs in mercury. An acoustic driver operating at high frequency (20 kHz) with a stroke of approximately 25 μm oscillates an attached test button of material that is immersed in mercury. In several seconds this device achieves the same number of cycles as does the SNS target in a day of operation. However, the pressure amplitude of the waves is believed to be up to three orders of magnitude smaller than in the actual case. Thus, although it is not meant to be an actual simulation, the test is a useful tool to correlate the known mechanical properties and processing treatments of the tested materials with their propensity for cavitation erosion.

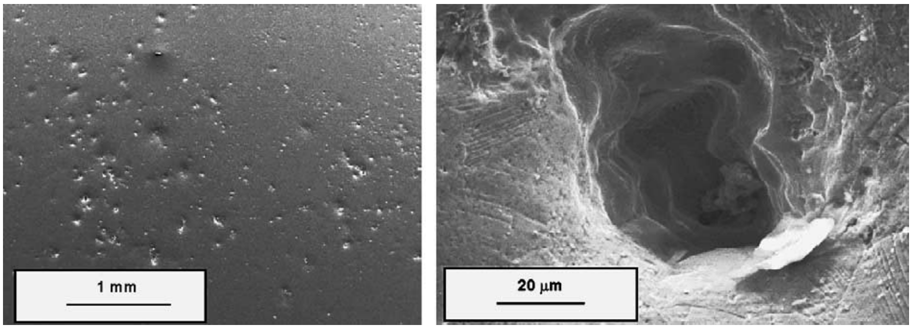

Fig. 2. Scanning electron micrographs of pits produced in 316 LN stainless steel after exposure to beam pulses in the LANSCE WNR. Left micrograph shows the appearance of the pitted surface and right micrograph shows the appearance of an individual pit and surrounding deformed material.

Fig. 3 shows results for one of these tests. The panel on the left shows that, after a 3 h exposure, the entire surface of the test button has a mottled appearance. On the scale of this micrograph the surface appeared smooth prior to the test. A higher magnification of a region of the surface of about 0.5 mm^2 is shown in the panel on the right. Larger features that may be described as pits are superimposed on the roughened surface.

3.2. Radiation effects

As mentioned above, the radiation effects work consists of both calculations and a variety of irradiation experiments in actual and simulated spallation environments. Calculated displacement damage together with He and H production by transmutation are summarized in [21]. Additional results on transmutation products other than He and H are given in [22]. Most of the calculated results obtained over the course of the materials R&D program are contained in a comprehensive report [23]. Detailed information is also given on the methods and assumptions employed in the calculations.

An overall impression of the extent of radiation damage to be expected in the target can be conveyed in a few key numbers. In the stainless steel at the front of the target on the beam center, a dose of 36 dpa will be accumulated in one full year of operation at 2 MW beam power. Nearly two-thirds of this dose is delivered by the spallation neutrons that originate from proton-induced reactions in the mercury, and one-third is caused directly by proton reactions with nuclei in the steel. It is also calculated that about 1400 appm/y of He and 19,000 appm/y H will be generated at the peak location in the steel. Nearly 90% of these transmutations are produced directly by proton interactions in the steel, with the remaining fraction produced by neutron interactions.

Considering that stainless steel loses ductility with increasing dose, with uniform elongations of less than a few percent being reached at typical doses of tens of dpa in reactor experiments, it can be concluded that the radiation damage target lifetime should be prudently set initially at less than one full power year. When factoring in the additional deleterious effects of gaseous transmutation products at the high levels quoted above, the loss of uniform elongation with dose may be more rapid [24,25]. For example, recent experiments where tensile elongations have been measured after irradiations in spallation environments showed more severe losses of ductility than for fission reactor environments [26–28].

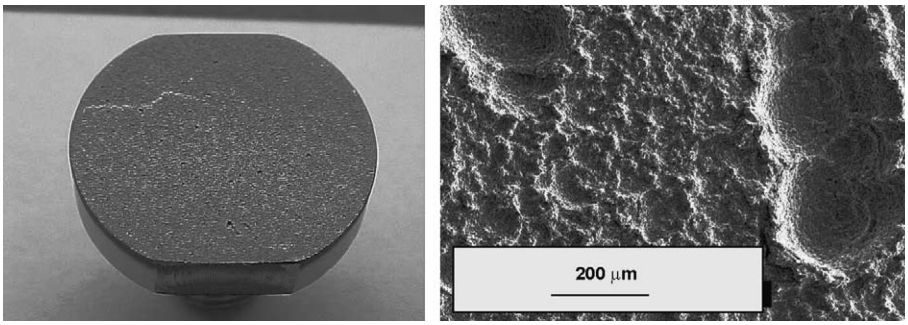

Fig. 3. Specimen surface after vibratory horn test. Left photograph shows visual appearance of specimen (large dimension 16 mm) and the right scanning electron micrograph shows details of mottled surface and of deeper features.

Additional factors in the SNS target environment suggest that conservatism in the initial target lifetime estimate is needed. These include the presence of fatigue loads, possible cavitation erosion as described above, and possible compatibility interactions with mercury in the presence of radiation. After analyzing all the experimental data available and taking into account the absence of current capability to perform testing that is prototypical for the SNS target material (see Table 1), we have recommended that the first target be removed for examination after no more than 5 dpa is accumulated at the peak damage location. This corresponds to somewhat more than seven weeks of full power operation. Whether cavitation erosion will limit the target lifetime to less than this interval is currently under intensive investigation.

Spallation irradiations carried out at the LANSCE facility have provided a wealth of information on mechanical properties of structural alloys. Fig. 4 shows data obtained in the SNS R&D program on yield strength (upper) and uniform elongation (lower) for type 316 LN austenitic stainless steel measured in tensile tests after irradiation [26]. The irradiations were carried out between 50 and 160 °C. For comparison, data from a collection of fission reactor irradiations on type 316 austenitic stainless steels below 200 °C are also shown. As mentioned above, it appears that the loss of ductility is more severe in a spallation environment than in fission reactor environments, at least for some of the data points.

Fig. 5 is a similar plot for a 9Cr-2WVTa ferritic steel. Here the reactor- and LANSCE-irradiated materials are identical and both sets of irradiations were carried out in the same program, rather than being a collection of data from a variety of sources as in Fig. 4. In addition, a similar comparison of this 9Cr-2WVTa ferritic steel with a larger database of ferritic steels along the lines of Fig. 4 above for austenitic steels has been presented [29]. Generally, the ferritic steels show a similar kind of increase in yield strength with dose as the austenitic steels. However, their uniform elongation is lower prior to irradiation and drops essentially to zero at less than 0.1 dpa, whereas the austenitic steels typically retain 20–30% uniform elongation at this low dose.

Another austenitic material, the superalloy Inconel 718, has also been the subject of research in the SNS radiation effects R&D program. It is being slated for service in the vacuum window in the beam line just upstream of the target. The plan to use it is based on satisfactory experience with a beam window of this material in the LANSCE facility. Generally, this alloy is used in the precipitation-hardened condition, where it is exceptionally strong. However, because it becomes embrittled at low dose when irradiated in this condition [27,30], we also irradiated it in the solution annealed condition [31]. These irradiations were carried out in the HFIR reactor. Figs. 6 and 7 show results for the precipitation hardened (PH) and solution annealed (SA) Inconel 718, respectively. Fig. 7 represents 'normal' behavior in the sense that it is similar to the behaviors in Figs. 4 and 5 (upper portions), i.e., the yield strength increased substantially with dose. In contrast the PH material did not show similar behavior. For this material, as the dose increased the material softened. This is a result of the dissolution of the γ' and γ'' precipitates that imparted the exceptional strength to the material. Similar softening behavior has been reported earlier [30] for Inconel 718 irradiated in the LANSCE facility. The

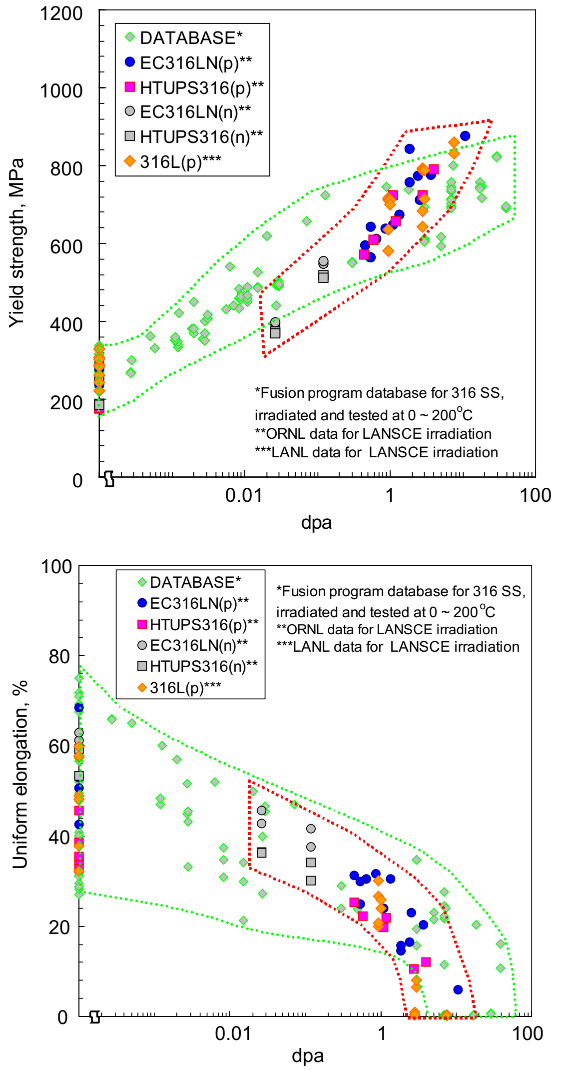

Fig. 4. Yield strength (upper) and uniform elongation (lower) measured in tensile tests on type 316 LN austenitic stainless steel after irradiation with 800 MeV protons.

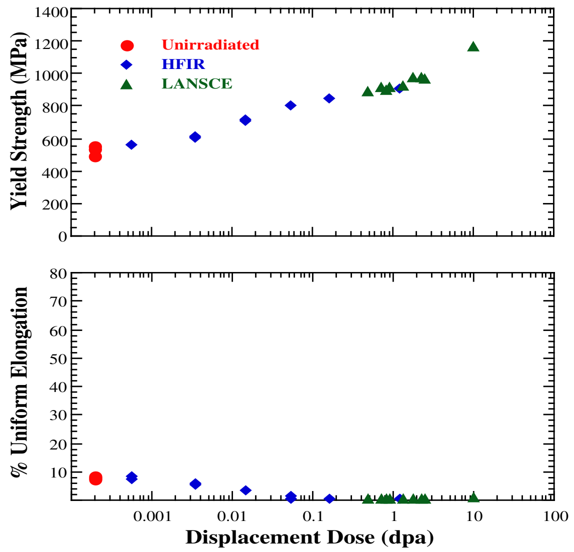

Fig. 5. Yield strength (upper) and uniform elongation (lower) for a 9Cr-2WVTa ferritic steel irradiated at the LANSCE facility as well as in the HFIR.

present study based on irradiations with reactor neutrons confirms the previous results and shows that the softening is not peculiar to spallation irradiations. In Ref. [30] although the material softened with increasing dose it became severely embrittled and failed by intergranular fracture, a trend that would normally be associated with increased hardening. In Fig. 6 it can be seen that for the HFIR irradiated material the uniform elongation dropped from greater than 15% in the unirradiated condition to near zero after 0.16 dpa.

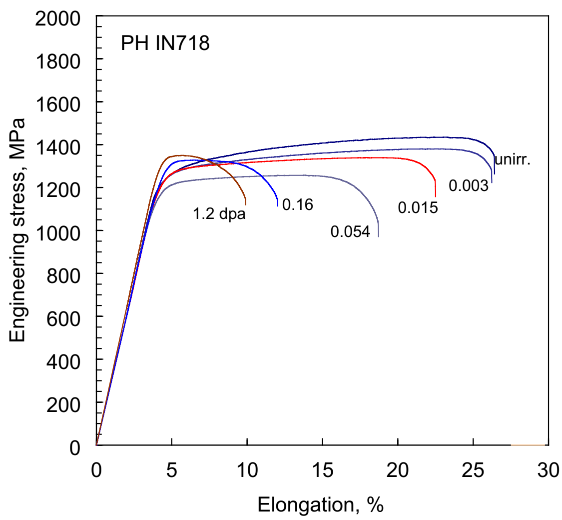

Fig. 6. Stress–strain behavior of Inconel 718 irradiated in HFIR to several doses in the precipitation-hardened condition.

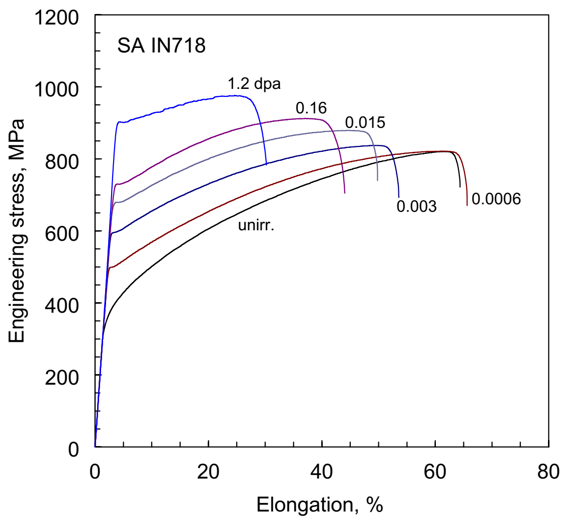

Fig. 7. Stress–strain behavior of Inconel 718 irradiated in HFIR to several doses in the solution annealed condition.

A mechanistic study was carried out to help understand the behavior of the PH Inconel 718 [32,33]. In particular the competition during irradiation between the known hardening effect of the accumulation of transmutation gases and softening by dissolution of the precipitates that initially imparted high strength to the alloy is of great interest. The study employed the ORNL Triple Ion Facility in which beams of Fe, He and H were applied singly or simultaneously.

Fig. 8 shows one key outcome from that work. Results from three different irradiations are shown, corresponding to Fe, He or triple-ion (Fe, He, H) beams. Both the triple-ion and the Fe irradiations gave softening as a function of dose. Gas was injected in the triple-ion irradiation at rates of 200 appm He/dpa and 1000 appm H/dpa. However, the He irradiation showed hardening up to a dose of about 10 dpa, after which softening was exhibited. A significant difference between the Fe only and the triple-ion irradiations on the one hand, and the He irradiation on the other hand was the amount of helium accumulated versus dpa. In the He irradiation approximately 14 at.% helium was injected to achieve 10 dpa, whereas only 0.2 at.% was injected in the triple ion irradiation and none in the Fe irradiation. The micrograph insets in Fig. 8 provide the key to explain the hardening and softening observations. Prior to irradiation the γ' and γ'' were present as shown by the micrograph inset at left. In all three types of irradiation these precipitates had disappeared by 10 dpa as shown by the micrograph insets at the right. The lower micrograph, corresponding to Fe only or triple-ion irradiation, showed no precipitates or bubbles. The upper micrograph, corresponding to the He irradiation, showed a microstructure packed with

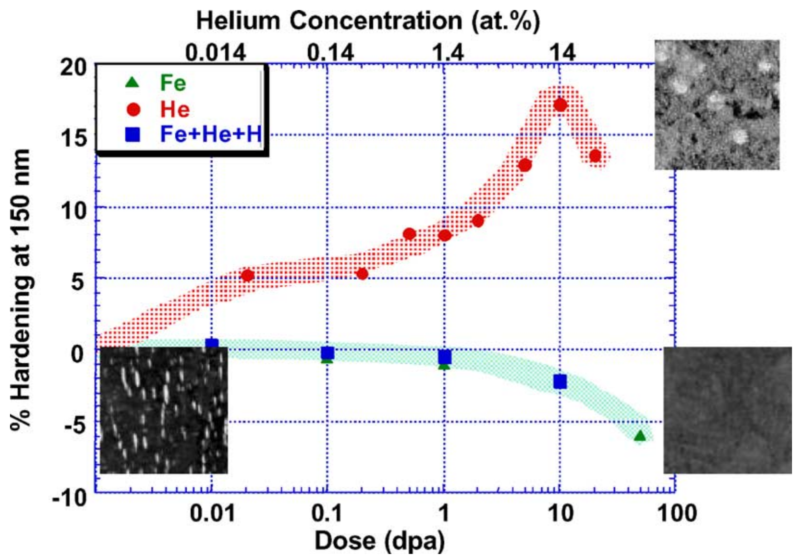

Fig. 8. Results from three different ion irradiations of Inconel 718, corresponding to Fe, He or triple-ion (Fe, He, H) beams. The top axis label applies only to the single beam He irradiation.

bubbles of order 1 nm in diameter. The conclusion from this work is that the rapid buildup of He with dose in the He irradiation, and the associated formation of small bubbles as barriers to dislocation glide, overtook the softening produced by the dissolution of precipitates and gave rise to a net hardening. Remarkably, this process led to a further increase in hardening beyond that imparted by the precipitates in what already could be characterized as a 'super-hard' alloy. It should be emphasized that this investigation is a fundamental offshoot of the applied R&D program. The actual levels of helium needed to produce the remarkable additional hardening observed here are too high to be of engineering interest in spallation target components.

3.3. Compatibility

Under this heading, work has been focused on two primary areas. The first is corrosion and, in particular, investigations into temperature gradient mass transfer. If such a process were pronounced, loss of mass, i.e., thinning of the target wall, would be of concern. Temperature gradient mass transfer generally occurs by the dissolution of material in higher temperature regions in contact with the liquid, with deposition of the material in cooler regions. Although the loop is closed, an overall equilibrium solubility in the liquid would not be established because of the temperature gradient; the process of mass transfer could go on continuously. Our previous work in this area was summarized in Ref. [5] and the more recent work is covered in a paper in these proceedings [34].

Most of the work on temperature gradient mass transfer employed thermal convection loops operating at a flow rate of approximately 1 m/min. Corrosion depths on 316 and 316 LN stainless steels and Inconel 718 coupons exposed to mercury for time intervals up to 5000 h were <15 μm. These results are encouraging since they may suggest that there would be negligible corrosion for engineering design purposes in the SNS target. There is a significant question, however, about whether such results can be relied upon to represent the behavior in a system where the flow rate will be of order 1 m/s. Therefore a forced convection loop that was initially used for thermal hydraulics testing [6], has been converted for materials corrosion testing in mercury at high flow velocities. Fig. 9 shows a schematic of the configuration of the loop. The coupons for investigation in the hot and cold regions of the loop are indicated at left, where the mercury temperatures in the hot leg were 250 °C, and in the cold leg were 100 °C. The coupons experienced mercury flow at approximately 1 m/s for 1000 h. The specimens comprised 316 LN stainless steel in a variety of surface conditions, which were devised to screen for susceptibility to corrosion in mercury. The work can be summarized to say that all specimens experienced negligible corrosion. Further details of the work are given in Ref. [34].

The other area covered under the compatibility heading addresses the effects of mercury on mechanical properties. Several sequences of tests have been carried out, including statically stressed U-bends, tensile, and fatigue tests. These three tests are viewed as progressively more severe in terms of the likelihood of mercury affecting mechanical response. Results in the first two

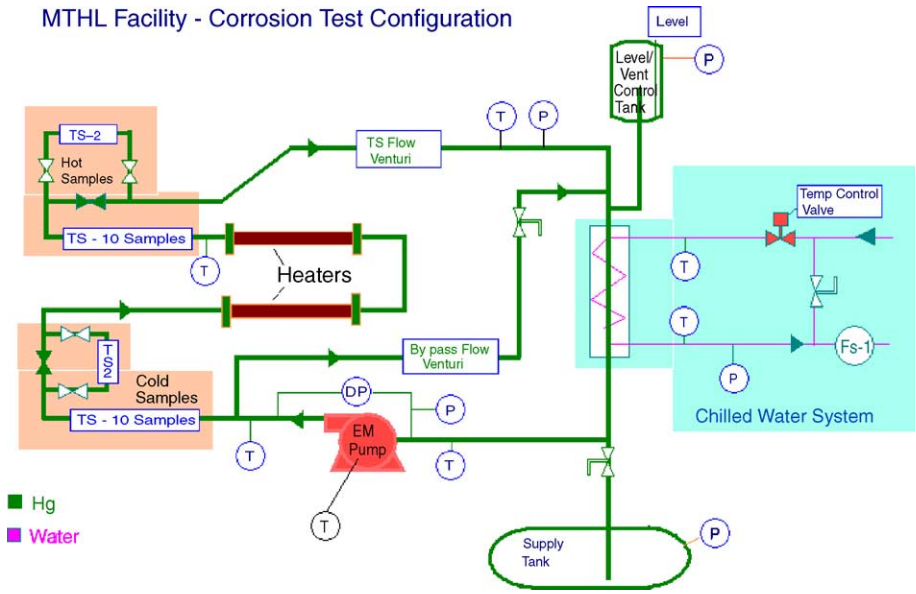

Fig. 9. A schematic of the configuration of the forced convection loop.

areas have been described previously [3–5,35], where little or no effects of mercury were found on mechanical properties. More recently, the emphasis has been on fatigue testing under various conditions in mercury and air environments. Some of the results have been published [36–38]. Additional results are contained in papers in the present volume [39,40]. A comprehensive report covering the entire fatigue test program is also available [41].

The fatigue work has given confidence that the time varying loads on the target will not lead to premature failure of the target module. Fluctuating loads on the structural material are imposed by the pressure waves caused by absorption of energy from the pulsed proton beam, and by beam shutdown and startup, for example. Loading frequencies vary from 60 Hz associated with the beam pulses to much lower frequencies related to beam trips and restarts and facility shutdown and startup. Higher frequencies also need to be considered. These arise from the rapid alternating compressions and rarefactions caused by reflections of the proton beam-induced pressure pulses. These frequencies may approach 1 kHz based on in-beam tests on reduced size mercury canister targets [42].

In the fatigue testing program wide ranges of conditions have been explored. These include maximum stresses up to more than 600 MPa, R ratios from −1 to 0.75, frequencies from 0.1 to 700 Hz, environments of both mercury and air, several applied load waveforms, testing carried out under load control and strain control, and different thermomechanical processing conditions for the 316 LN stainless steel. Here R is defined as the ratio of the minimum to maximum stress in each repetitive cycle of the fatigue test. Figs. 10 and 11 show results that summarize some salient parts of the work. Fig. 10 shows a series of tests plotted as alternating stress vs. cycles to failure. Results are shown for specimens tested in both air and mercury. In the air tests the specimens were cooled by flowing low temperature nitrogen gas over them to remove the heat imparted by plastic deformation at the high frequency of 700 Hz. Here the fatigue cycle frequency was higher by more than a factor of ten compared to the SNS pulse frequency of 60 Hz. These tests permitted data collection on an accelerated schedule. In these tests the R ratio was 0.1. Under these conditions it can be seen that mercury did not shorten the fatigue life in comparison with air for alternating stress amplitudes ranging from approximately 230 MPa down to the apparent endurance limit

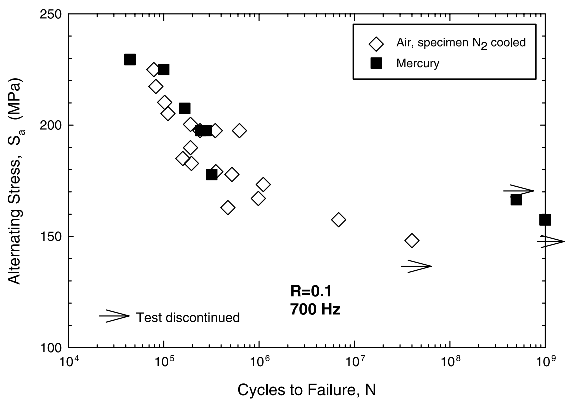

Fig. 10. Fatigue lives in air and mercury at 700 Hz with $R = 0.1$.

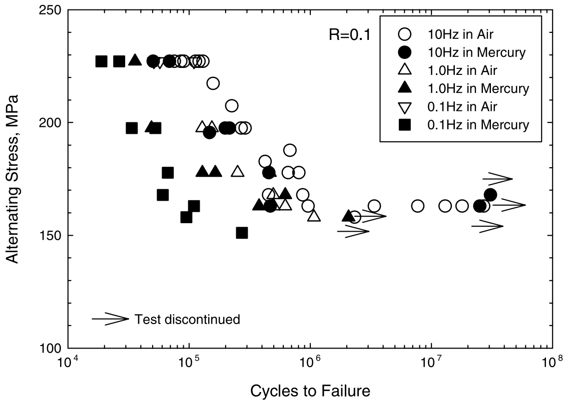

Fig. 11. Fatigue test results for $R = 0.1$ at frequencies of 0.1–10 Hz in air and mercury.

of approximately 150 MPa, i.e., for any stress level tested. At the latter stress amplitude the test in mercury was stopped without failure at 10^9 cycles. This corresponds to about 193 days of SNS operation, and is indeed an encouraging result.

At frequencies of 1 and 0.1 Hz in tests with R ratio of 0.1 there does appear to be a shorter fatigue cycle life in mercury than in air at stresses higher than the yield stress. However, at 10 Hz the fatigue lives are comparable. Fig. 11 shows these results. Under normal operation in the target the stresses will not be allowed to reach the yield stress, so these results can also be interpreted as encouraging.

3.4. Future work

The above sections have highlighted progress in the materials R&D program. It is now considered that the feasibility of the chosen SNS target design has been established. Gains in knowledge described above, however, have brought with them the background to see new needs and to ask further detailed questions. Thus future work should aim at optimizing the service life. Along the lines of the workshop objectives, participants were encouraged to discuss open questions and recommend future work. The present section offers several recommendations based on accumulated knowledge and perceived open questions. In each of the three areas of emphasis viz., cavitation erosion, radiation effects, and compatibility work is needed to both understand basic mechanisms and to settle questions related to applications. There are many questions of this nature. One key question from each area is described below.

3.4.1. Cavitation erosion

Is there a figure of merit for materials that will correlate results for mercury tests and reliably guide engineering improvements to reduce cavitation erosion in pulsed spallation targets? Various suggestions gleaned from the literature are hardness, resistance to abrasion, and a factor derived from combined measurements on eroded surfaces and from microscopic characterizations of the eroded particles released into the liquid. The latter figure of merit can be expressed as $H^{-3/2}E^{-2}$, where H is the Vickers hardness and E is the Young's modulus of the material [43]. These figures of merit often provide reasonable correlations for resistance to erosion in vibratory horn tests in water. However, detailed examination of the results in Refs. [11–19] show that the figures of merit suggested above do not correlate the observed results consistently. Is there an alternative figure of merit that can correlate the observed results? Guided by such a measure, if it exists, what is the likelihood of finding a materials solution to the pitting problem?

A broader question naturally arises. If a materials solution to the pitting problem is found, will that material have acceptable properties with respect to radiation damage and compatibility with mercury? We have built up a large base of knowledge that shows that type 316 LN stainless steel has very good properties with respect to resistance to radiation damage and resistance to mercury corrosion under the conditions applicable to SNS. However annealed 316 LN does not appear to have satisfactory performance with respect to cavitation erosion. On the other hand, selection of a new alloy based on cavitation erosion performance alone may not be a net gain. Sufficient testing and evaluation of a new alloy for overall performance would take perhaps five years at a minimum. This interval does not meet the current schedule. In recent tests, however, cold-worked 316 LN has given much better performance than its annealed counterpart. Since the cold-worked version can reasonably be expected to maintain its good performance under irradiation and in interactions with mercury, this may be the best materials solution overall. However, it should be noted that the uniform elongation of the cold worked material is very low even in the unirradiated state at the expected SNS operating temperature, although the total elongation remains in the range 10–20%. More work is required to come to a definitive answer.

3.4.2. Radiation effects

Recent work suggests that ductility in post-irradiation tests of stainless steels under spallation conditions [27] may be degraded more rapidly with dose than in fission reactor irradiations. What is the origin of this effect and does it have any practical consequences for the performance of stainless steels in a spallation target? Generally, spallation irradiations produce much more transmutation helium and hydrogen than fission reactor irradiations. There is some evidence that this higher production may be implicated in this degradation of ductility. These results need to be confirmed and further experiments devised to understand the origin of the effect and to determine its practical consequences.

3.4.3. Compatibility

Much of the compatibility work, including both temperature gradient mass transfer and fatigue tests, has shown small or negligible effects of mercury on performance of type 316 LN stainless steel. However, it is also a general observation that in much of this testing the stainless steel has not been wet by the mercury, even at temperatures well above the planned operational temperature range of the SNS target. Without wetting it is to be expected that interactions with the steel surface would be reduced or eliminated. An important question is to what degree compatibility testing results under conditions of no wetting are relevant to the actual target. Perhaps the most significant open question in this respect is whether irradiation and/or cavitation will have an effect on wetting behavior. Hypothetical arguments can be made that simultaneous irradiation and contact with mercury may cause interfacial reactions not seen without irradiation. If wetting occurs under irradiation, how will fatigue and temperature gradient mass transfer performance be affected? Tests now underway in the SINQ of specimen-containing mercury-filled capsules prepared by ORNL, will be examined to help determine the answer to this question. However, only information on corrosion behavior at higher temperatures will be obtained. Further experiments must be devised if information on mercury effects on mechanical properties, and if compatibility behavior at lower temperatures are to be determined.

4. Summary

The research and development program for the structural material of the mercury target module in the SNS covers three primary areas. These are cavitation erosion, radiation effects, and compatibility with mercury. The material with which the target module will be constructed is type 316 LN stainless steel. The program was begun at a low level in 1995 with the pre-conceptual design of the facility. Extensive testing, analysis of data and calculations have been carried out over the last five years. Twelve major types of experiments are included in the program, as summarized in Table 1. In addition, thorough radiation damage and transmutation calculations for He, H and heavier reaction products have been carried out. Collaborations among groups in the United States and with international partners have been key to high productivity of this program.

Based on the information developed for radiation effects and compatibility with mercury, analysis indicates that the target will meet its intended service requirements. In the past year and one half the new issue of cavitation erosion has been included in the program. Although there is no prototypic environment in which to carry out experiments, both in-beam and laboratory experiments indicate that cavitation erosion may occur in the target. Intensive research efforts are now underway to determine whether cavitation erosion will limit target lifetime to a level below the lifetime limit set by radiation effects.

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