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METAL HYDRIDE WALL STRESS MEASUREMENTS ON A FOUR-INCH SHORT (FISH) BED

E. G. Estochen and J. E. Klein

Savannah River National Laboratory: Aiken, SC 29808,james.klein@srs.gov

A 38 cm (15 inch) long metal hydride bed fabricated using 11.4 cm (4.5 inch) O.D., standard schedule 316/316L stainless steel pipe was fitted with 22 strain gauges to measure tangential and longitudinal stress resulting from hydride absorption and desorption cycling. Tests were conducted using two different $LaNi_{4.25}Al_{0.75}$ metal hydride fill-levels in the bed.

Tests conducted with hydride filled to two-thirds (1.75L) of the 2.63L total bed volume resulted in a maximum stress less than one-third of the pipe's ASME Code allowable, for hydride absorption up to a hydrogen-to-metal ratio (H/M) of 0.86. After 15 absorption/desorption tests and hydride passivation, examination of the bed interior revealed a significant decrease in particle size and increase in hydride height. The second fill level had 0.4L of fresh hydride added to the bed's cycled hydride material, and 56 absorption/desorption tests, up to a gas loading of 0.83 H/M performed. Second fill tests resulted in maximum stresses less than 40% of the ASME Code allowable. Post-test bed radiographs showed a further increase in the apparent hydride fill height, and internal component deformation.

I. INTRODUCTION

For ten years, the Savannah River Site (SRS) Tritium Facilities have used metal hydride storage beds[1,2] with 12.6 kg of $LaNi_{4.25}Al_{0.75}$ for process gas absorption, storage, and desorption. These 1st generation (Gen1) storage beds contain the metal hydride in a 7.62 cm (3 inch) pipe process vessel (PV). A 2nd generation (Gen2) metal hydride bed has been developed,[3,4] using the same pipe sizes and hydride alloy as the Gen1 beds, and will go into production use in 2004.

The Gen2 bed, developed as a Passively-Cooled, Electrically heated hydride (PACE) Bed, thermally swings the bed utilizing electric heaters for desorption and much lower forced atmosphere cooling flow rates than the Gen1 beds for gas absorption. These beds are also referred to as Forced-Atmosphere (glove box nitrogen) Cooled, Electrically heated (FACE) Beds.

A 3rd generation (Gen3) production metal hydride storage bed is under development that will utilize 11.4 cm (4.5 inch) O.D., standard schedule pipe for the process vessel. One aspect of hydride bed development is to determine the PV wall thickness required to withstand the volumetric expansion of the metal hydride during hydrogen absorption. Wall stress measurements during hydride cycling were performed on a 7.62 cm (3 inch) pipe PV during Gen1 bed development[5], but applicability of the results were deemed geometry specific. The purpose of this work was to measure wall stresses during hydride cycling on a 11.4 cm (4.5 inch) O.D., schedule 40 pipe PV, and determine if the stresses would meet pressure vessel code allowable design limits.

II. BACKGROUND

The Gen1 bed length was approximately 0.91 m (3 feet) and contained 12.6 kg of the $LaNi_{4.25}Al_{0.75}$. The Gen2 bed length increased to approximately 1.22 m (4 feet) long even though it used the same PV pipe and was filled with the same hydride mass and alloy composition as the Gen1 bed. The increased Gen2 bed length was necessary to compensate for PV volume occupied by aluminum foam, divider plates, heaterwells, thermowells, and the in-bed accountability U-tube.[3]

Locating Gen2 beds in a glove box with over 1.2 m of clearance for heater removal and replacement was a challenging design issue. Use of 11.4 cm (4.5 in) O.D., schedule 40 pipe for a Gen3 bed results in a much shorter, 12.6 kg capacity metal hydride bed. The goal of Four-Inch Short Hydride (FISH) Gen3 bed development is to reduce bed length to approximately 0.61 m (2 feet).

PV stress from hydride expansion during gas absorption, is highly dependent on bed geometry, percentage of volume filled, and distribution of the hydride powder within the PV volume.[6,7] The purpose of this work was to fabricate a bed out of 11.4 cm (4.5 inch) O.D., standard pipe, measure the wall stresses exerted by the hydride on the PV during gas cycling, and determine if schedule 40 pipe was of sufficient strength for production bed use.

III. EXPERIMENTAL

The general configuration of the prototype stress measurement bed, designated SB01, is shown in Figure 1. The 0.392 m (15-7/16 in) long bed was fabricated from 11.4 cm (4.5 in) O.D., schedule 40, 316/316L stainless steel pipe and pipe caps and had an internal volume of approximately 2.63 L.

The “header” end pipe cap was penetrated horizontally by a 0.95 cm (3/8 in), schedule 10 pipe used as a heaterwell and a 1.27 cm (0.5 in) O.D. sintered metal filter tube for gas transfer into and out-of the bed. The heaterwell and filter tube extended to within 3 cm of the other end cap. The bed centerline was 1.9 cm below and 3.5 cm above the filter tube and heaterwell centerlines respectively.

Opposite of the header end, a 1.27 cm (0.5 in) Cajon® VCR gland fitting, was attached normal to the end cap surface 3.5 cm above the bed center. The fitting was used as a fill-port, access point for a fiber optic camera, and inserting a thermocouple (TC) into the hydride powder.

The bed support fixture used rollers to facilitate free bed thermal growth by placing one end cap against a fixed vertical surface while leaving the other end cap unrestrained. Longitudinal bed displacement was measured with a linear voltage displacement transducer (LVDT) placed against the unrestrained end cap.

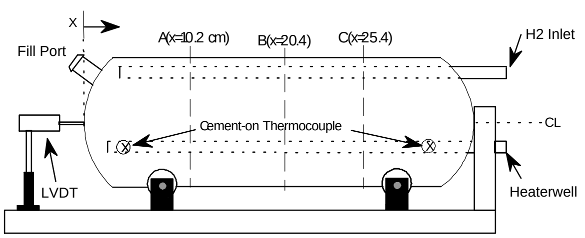

Fig. 1. SB01 General Test Configuration.

High temperature epoxy was used to bond strain gauges (SGs) to the bed perimeter at Figure 1 section lines “A”, “B”, and “C”. Tangential stress SGs were at radial positions of 0°, 90°, 180°, and 270°, as viewed from the fill port end, for all three sections. Section B had four additional tangential SGs at 45°, 135°, 225°, and 315°. Longitudinal stress SGs were attached at the 90° and 270° positions on all three sections.

Each SG was wired as a one-quarter Wheatstone bridge with a three-wire lead configuration to minimize lead wire resistance changes with temperature. The SGs were matched to bed material for thermal expansion considerations, but the quarter-bridge circuit did not compensate for gage resistance changes due to temperature variations. Due to this limitation, strain changes were only calculated when the bed temperature was within ±1°C of the initial test temperature.

The data acquisition system recorded SG data, V_g, the ratio of circuit output-to-excitation voltage, as a function of time. V_g data just prior to gas cycling, V_{g0}, and during testing, V_{gt}, were used with the SG gage factor G_F, to compute the change in strain, ε, (μstrain) using

$$\varepsilon=-4000\,(V_{gt}-V_{g0})/[G_F(1+2\,(V_{gt}-V_r))] \quad (1)$$

The tangential stress, σ_T, was computed using

$$\sigma_T=2\varepsilon EA_i/(2-\nu) \quad (2)$$

where ε is from Eqn. 1, E is the pipe’s Young’s modulus, ν is Poisson’s ratio, and A_i is a SG specific scale factor. Longitudinal stress, σ_L, was computed using

$$\sigma_L=\varepsilon EA_i/(1-2\nu) \quad (3)$$

A_i values were calculated during SG calibrations. SG calibrations had the bed filled with argon up to 4.93 MPa (700 psig) argon and the SG response compared to that calculated using standard cylindrical pressure vessel equations. Ai values for Eqn. 3 were taken as unity due to close agreement between measured and calculated stresses obtained during pressure calibrations.

New, as received from Ergenics, $LaNi_{4.25}Al_{0.75}$ metal hydride material (less than 1.68 mm) was used for these tests. The initial 1.75 L (7.88 kg) bed fill was roughly 67 volume percent (63 height percent) while an additional 0.4 L (1.78 kg) of new material for the second fill would give a calculated 82 volume percent (76 height percent) if added to the as- received material before hydride absorption/desorption.

The bed was rotated about its centerline several times to evenly distribute the powder within the bed. A fiber optic camera inserted into the fill port was used to determine if the powder was level by comparison to horizontal lines scribed on the inside of the end cap. The same leveling method was used for both bed fills.

A gas absorption/desorption manifold was used for loading and desorbing the bed. Protium was supplied to calibrated volumes (188 L) and fed through a mass flow controller (MFC) for absorptions. Desorption gas went through a MFC and either through a pump to the calibrated volumes or through another pump and vented. All loading H/M values used pressure-volume-temperature (PVT) calculations. Desorption H/M values used MFC-time data unless desorption gas volumes allowed collection in the calibrated volumes which allowed PVT calculations to be used.

For the first hydride fill, five absorption/desorption cycles, consisting of 15 loading/unloading steps, were performed where the bed ranged from nominally 0.9 H/M to 0.1 H/M. For the 5th bed cycle, multiple absorptions steps were made before reaching the maximum bed filling and multiple desorptions steps made for bed unloading. A step started with the bed at ambient temperature and concluded when the bed returned to ambient temperature.

After bed desorption/bake-out and hydride passivation with air at ambient temperature, 0.4 L of new hydride was added to the bed. The second fill was subjected to 19 cycles consisting of 56 absorption/desorption steps.

After completion of these hydride cycles, the bed was baked-out and subjected to six thermal cycles with each simulating a desorption temperature profile. Then, five absorption/desorption cycles were performed with the bed flipped "up-side-down". The bed was then baked-out and passivated with air before complete hydride removal from the bed. Six more thermal cycles were then performed on the empty bed.

IV. RESULTS

For stress comparison, the ASME code normal operating allowable of 115 MPa (16.7 KSI) for 316L stainless steel was used.[8] Absorptions performed with the first bed fill resulted in a maximum σ_T of 17 MPa (2.4 KSI) tension at the section "A", 0° position, and a maximum σ_L of 32 MPa (4.7 KSI) compression at the section "A", 90° position. The maximum σ_L occurred during the first absorption cycle, when the hydride material was likely to experience the greatest amount of particle size reduction. Subsequent first fill tests, showed a gradual reduction in the maximum compressive σ_L value to a value stable and less than 14 MPa (2 KSI).

In general, absorptions resulted in tensile stresses on the sides of the bed (0° and 180° positions) and compressive stresses at the top of the bed. Failure of SGs on the bed bottom did not facilitate assessment of the general response, but other SGs indicated minimal tensile to slightly compressive stresses on the bottom -- within the limits of the SG measurements. SG output error due to slight variations between start and end point temperatures, or drift due to periods of elevated temperature, was estimated as 3 MPa (0.5 KSI).

For the second hydride fill, post-absorption stresses did not increase considerably. The maximum σ_T value was 39 MPa (5.6 KSI), tension, at the section "C", 180° position, and the maximum σ_L value was 30 MPa (4.4 KSI), compression, at the section "B", 90° position. The first fill trend of compressive stress on the top of the bed, and tensile stress on the sides was observed for the second hydride fill. Compressive stress was obtained on the bed bottom.

Figure 2 shows the bed's stress distribution around the perimeter for a typical absorption for the second hydride fill and for H/M>0.8. Compressive stresses (negative values) were found at the top, empty portion, of the bed. Tangential stresses increased to maximum tensile values at the bed equator, then decreased to a nominal tensile value at the bottom of the bed. Similar stress distributions, but with smaller values, were found for the first hydride fill.

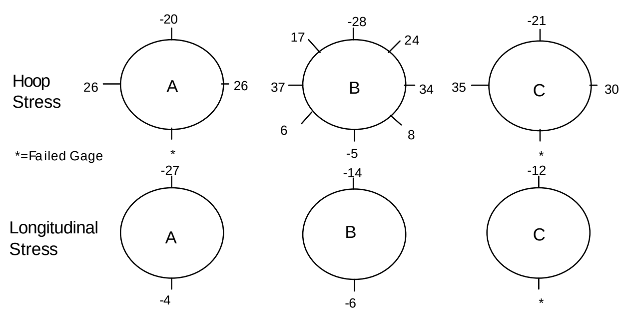

Fig. 2. Typical Post-Absorption Stress (MPa) Distribution for Second Metal Hydride Fill and H/M>0.8.

Figure 3 shows second fill, bed stress changes during absorption and desorption . Absorption induced stresses did not increase significantly until Q/M exceeded 0.6, but small incremental desorptions result in a rapid wall stress reductions. A positive SG drift was found after desorptions and was obvious when compressive (negative) stresses for the fully loaded bed transitioned to tensile stresses as the bed was desorbed.

V. DISCUSSION

Inspection of the cycled hydride before adding fresh material for the second bed fill showed a significant reduction in particle size, but a larger occupied volume. The second hydride fill resulted in partial hydride coverage of the filter tube. Radiography after 19 absorption/desorption and six thermal cycles with the second hydride fill showed significant deformation of the filter tube by the increased volume of the hydride material. Radiography also showed the hydride material did not flow into the empty space at the top of the bed when the bed was rotated "up-side-down": even after repeated impacts with a rubber mallet and five additional absorption/desorption cycles.

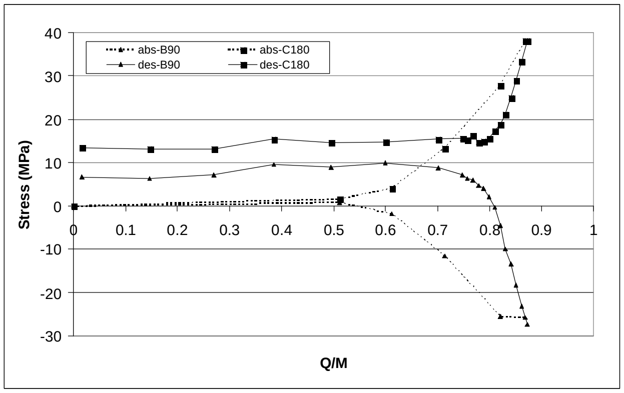

Fig. 3. Typical Hoop Stress Stress (MPa) Variations with Q/M for Bed Absorption and Desorption.

The strain gage material, Constantan, was determined to have poor long-term stability. A positive SG drift was found during the test program and attributed to SG exposure to elevated temperatures, especially after bed heating for gas desorptions. The drift with temperature was confirmed by the lack of change in SG output just before and just after hydride removal from the bed. Thermal SG drift was further confirmed by thermally cycling the empty bed and observing increased SG output. SG drift during absorptions was smaller than during desorptions due to the lower SG temperatures.

VI. CONCLUSIONS

A 11.4 cm (4.5 in) O.D. by 0.6 cm (0.237 in) thick wall prototype bed, with a nominal 80 percent bed fill and hydride loading greater than 0.8 H/M, experienced hydride expansion induced stresses less than 40 percent of the ASME allowable for 316L stainless steel. These results show the pipe size and thickness are adequate for process bed fabrication. Thinner walled beds, for improved thermal swing response, may be possible but verification stress measurement tests would be needed.

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