HYDRIDING-INDUCED WALL STRESS EVALUATION OF A PROTOTYPE FOUR-INCH SHORT (FISH) TRITIUM HYDRIDE BED

K. J. Heroux[1,]* and E. G. Estochen[1]

1. Savannah River National Laboratory, Aiken, SC 29808

***Corresponding author:**
Savannah River National Laboratory
Savannah River Site, Building 999-2W, C23
Aiken, SC 29808
803-514-0472
katie.heroux@srnl.doe.gov

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ABSTRACT

The hydriding-induced wall stress evaluation of a prototype Four-Inch SHort (FISH) tritium hydride bed revealed that the advanced design features do not result in additional strain on the process vessel walls during simulated operation. The maximum tensile wall stress measured at high hydrogen loadings (H/M>0.7) was determined to be <40% of the ASME allowable limit for 316L stainless steel. Variation in wall stress with hydride loading was also examined via stepwise protium absorption and desorption. Minimal hydriding-induced wall stress was observed in the optimal operating range of the hydride material. The results described herein are in good agreement with previous studies on similar hydride storage beds without the advanced design features. Completed verification of ASME compliance for the FISH bed is a major milestone in its qualification for tritium service.

I. INTRODUCTION

The Savannah River Site (SRS) Tritium Facilities (TF) have used metal hydride beds to store, separate, transport, compress, and purify hydrogen isotopes for over 20 years.[1,2] The first generation (Gen 1) hydride beds utilize 12.6 kg of $LaNi_{4.25}Al_{0.75}$ (or LANA.75) and require a hot and cold nitrogen (HCN) system for operation. The second generation (Gen 2) hydride bed uses the same pipe size and LANA.75 alloy as the Gen 1 bed but was developed to thermally swing the bed using electric heaters during desorption and forced atmosphere cooling during absorption.

The Four-Inch Short (FISH) hydride bed, which is the third generation (Gen 3) of hydride beds, is currently in development and was designed as a direct replacement for the Gen 2 bed.[1] The FISH bed offers the same hydrogen storage capacity as the Gen 2 bed in a shorter bed design (0.61 m) using 4-inch standard schedule pipe, which allows for a smaller glovebox footprint and full-bed-length cartridge heater replacement. Additionally, the FISH bed utilizes the lower pressure $LaNi_{4.15}Al_{0.85}$ (LANA.85) hydride material, which is expected to improve absorption rates and reduce gas lost during inert evacuation. The advanced design features of the FISH bed will significantly reduce operating costs by eliminating the need for the HCN system; simplifying bed activation and installation processes; improving bed performance and efficiency, In-Bed Accountability (IBA), and end-of-life bed removal; and facilitating potential He-3 recovery.[1,2]

Because metal hydride materials expand upon hydrogen absorption, determining the process vessel (PV) expansion stresses to ensure adequate wall thicknesses is an important aspect of hydride bed development. In 1992, direct wall stress measurements on a prototype hydride storage bed for the Replacement Tritium Facility (RTF) determined that upon expansion a hydride material will exert force against the PV walls rather than act as a fluid by flowing into the void space to equalize the pressure. Although this type of wall stress analysis has been performed during the development of earlier generation hydride beds, PV stress resulting from hydride material expansion is highly dependent on bed geometry, bed internal features, hydride material, and fill level/distribution of the material within the vessel.[3] Thus, in 2005, wall stress measurements on a bed (38 cm in length) constructed of 4-inch standard schedule pipe (SB01 bed) were reported at two different LANA.75 hydride fill levels. The tests concluded, as part of ASME Code design, that this pipe size could sufficiently withstand the hydriding-induced wall stresses and would be adequate for FISH bed fabrication.[2] The design and fabrication of the prototype FISH bed have been previously described.[1]

The added design features of the FISH bed, including a cellular structure with aluminum heat transfer foam and porous divider plates to partition the hydride material, heater wells, central thermowell, gas inlet filters, IBA U-tube, and external heat transfer fins, may impart unknown stress on the PV walls during hydride absorption/desorption cycling. Therefore, a confirmatory hydriding-induced wall stress evaluation of the prototype FISH bed to ensure the ASME Code compliance of the bed design was performed and is discussed herein.

II. EXPERIMENTAL

II.A. Strain gage installation and calibration

Karma (or K-alloy) strain gages were selected for the wall stress testing because of their greater output stability when subjected to prolonged thermal cycling. The selected gages (0.64 x 0.95 cm, model #WK-09-250BG-350) were purchased from Vishay Micro-Measurements and were fully encapsulated with high-endurance lead wires and exhibit 350 Ω resistance, a strain range of ±1.5%, a temperature range of -269°C-290°C, self-temperature compensation matched for attachment to 304 stainless steel, and a gage factor of 2.03 ±1%.

Twenty-six strain gages (20 hoop and 6 longitudinal) were applied to the surface of the FISH bed via a 2-part heat-curing epoxy (M-Bond 610, Micro-Measurements) at ~205°C for ~2 h. After curing and cooling, the strain gage leads and data wires were soldered to the terminal pad contacts. The strain gages were wired in a 3-wire quarter bridge configuration to compensate for lead wire resistance changes with temperature. The strain gage layout, influenced by earlier hydride bed testing, is depicted in Figure 1, where “H” denotes hoop strain and “L” denotes longitudinal strain. Each pattern consists of 2 longitudinal gages positioned at the top and bottom of the bed in addition to 4 hoop gages (8 in pattern E) evenly spaced around the circumference of the bed.

Calibration factors were determined for each strain gage using the hoop and longitudinal strain calculated from bed internal pressure loading (0-0.7 MPa argon) with the gage output voltage data captured at constant pressure/temperature. The strain data obtained were plotted with expected strain values and used along with curve-fit results to obtain an average calibration factor for each gage to use when converting output voltage to strain.

II.B. Protium absorption/desorption

The FISH bed, filled with 13.6 kg of LANA.85, was sufficiently activated by protium absorption/desorption cycling prior to the wall stress evaluation. For the hydriding-induced wall stress measurements, the equilibrium strain gage responses were monitored at different hydrogen to metal atom ratios (H/M). A full-scale hydride bed test system was used to cycle known amounts of protium gas on and off the bed. Several measurements at maximum loading (H/M=0.77) were first performed to determine the largest wall stress expected during cycling. An incremental desorption (18 steps) to H/M=0.05 was then performed. Because the strain response is measured as the difference between the initial and final gage output voltages, which are highly sensitive to variations in temperature, care was taken to ensure that the bed surface temperature was approximately equal (~22°C) at the beginning and end of each step to minimize the impact of temperature differences on stress/strain calculation results. After the final desorption aliquot was removed, a 9-step protium absorption was performed (returning to an H/M of 0.77) to demonstrate the repeatability of individual strain gage measurements and examine for hysteresis. For this stepwise absorption, a "step" refers to a partial loading to reach a target H/M value.

All bed loadings were determined by pressure-volume-temperature (PVT) calculations. Protium was loaded and unloaded through a gas inlet tube that only penetrates into the first zone/cell of the FISH bed.[1] The other gas tube, which runs the full length of the bed, was blanked off during these tests. Insulation consisting of Kaowool and aluminum foil was wrapped around the bed for faster and more even heating by reducing heat loss to the aluminum bed support structure and surrounding air. The bed was cooled in ambient air with nitrogen gas flowing through the internal IBA U-tube. All measurements were performed in a temperature-controlled box to minimize the effects of laboratory temperature fluctuations. The bed surface typically reached a temperature of ~120°C during absorption/desorption with the hydride material temperature reaching ~170°C. The hydriding-induced wall stresses were calculated from the strain gage voltage output change at each absorption/desorption equilibrium step.

II.C. Calculation of wall stress

Prior to conversion to stress for comparison to ASME Code allowable limits, the quarter bridge circuit time-dependent output voltage was used to calculate strain. For determination of either longitudinal or hoop microstrain ($\mu\varepsilon$), the following equation was used to obtain direct gage strain output (e.g., uncalibrated):

$$\mu\varepsilon = -4*(1x10^{6})[(V_t-V_o)/V_{in}]/(GF*[1+(V_t-V_o)/V_{in}]),$$

where V_{in} = 3300 mV, GF (gage factor) = 2.03, V_o = no load or t=0 gage output voltage, and V_t = instantaneous gage output voltage at time t.

After calibration of the gages using internal pressure loading, where the expected pressure induced strain was calculated using thick wall vessel equations for comparison to the actual gage output and regression performed to obtain individual gage calibration factors, the individual gage strain equations were defined as follows:

$$\text{Gage “x” } \mu\varepsilon = -4*(1x10^{6})[(V_t-V_o)/V_{in}]/(\text{Calibration Factor}*2.03*[1+(V_t-V_o)/V_{in}])$$

After computation of calibrated strain, conversion to stress was performed using the following general equations:

$$\sigma_{hoop} = \varepsilon_H E[1+\nu((1-\nu)/(2-\nu)]/(1-\nu^2) \text{ psi;}$$

$$\sigma_{longitudinal} = \varepsilon_L E[1+\nu(2-\nu)/(1-\nu)]/(1-\nu^2) ;$$

where E (Young's Modulus for stainless steel) = 28×10^6 psi, ν (Poisson's ratio for stainless steel) = 0.28, ε_H = hoop Gage "x" $\mu\varepsilon$ multiplied by 1×10^{-6}, and ε_L = longitudinal Gage "x" $\mu\varepsilon$ multiplied by 1×10^{-6}. The stresses obtained from these equations for each gage could then be directly compared to ASME limits. It should be noted that gages DH3 and GH4 produced non-repeatable data from the initial cyclic pressure calibration, thus they were not used to assess bed stress conditions.

At the conclusion of the wall stress testing, bed internal pressure calibration of the strain gages was repeated to compare initial and final calibration factors. These results, along with an evaluation of all "zero load" strain gage data at room temperature, confirmed that the following 10 strain gages remained fully functional (did not require calibration factor adjustment) throughout the testing period: DH1, EH1, EH5, EH8, FH1, FH3, GH1, GH3, EL2, and FL2. (Deterioration of strain gage response is typical over prolonged thermal cycling due to bond degradation and resistance changes.) These 10 gages (8 hoop and 2 longitudinal with at least 1 gage from each pattern) were deemed sufficient for a complete wall stress evaluation of the FISH bed prototype design, particularly for identifying the maximum sustained hydride expansion stress for evaluating vessel wall thicknesses.

III. RESULTS AND DISCUSSION

A full wall stress evaluation of the FISH bed was performed to ensure that the added design features of the prototype bed (particularly the heat transfer foam and filter plates) would not result in additional stress on the vessel walls upon hydriding. Ultrasonic and radiographic evidence of localized plastic deformation of the external walls of a similar type of hydride bed near divider plates has been previously reported.[4] Thus, the strain gages in patterns D, E, and F (see gage layout in Figure 1) aligned with the porous metal divider plates inside the bed represent the points at which the largest strain is expected due to the presence of solid hydride material between the vessel wall and rigid divider. The gages in pattern G are not aligned with an internal divider plate and can thus be used to determine if additional strain exists proximate to the divider plates. The internal aluminum heat transfer foam is expected to potentially reduce stress levels because (1) it ensures a more even distribution of the hydride material within the bed, leading to more uniform expansion, and (2) the hydride material may compress the foam as it expands, as opposed to expanding solely against the vessel walls.

Figure 2a shows the variation in hoop stress with H/M for a stepwise protium desorption. As expected, the longitudinal stress levels were <50% of the maximum hoop stress, thus they have been omitted from the figure. The maximum post-equilibrium wall stress was observed at strain gage GH1 with a value of 35 MPa at H/M=0.77, which is in excellent agreement with the magnitude and location of the maximum stress measured during preliminary testing at the same hydride loading level. For ASME Code comparison, 316L stainless steel (welded pipe) has an allowable stress of 98 MPa for temperatures up to 100°F (Ref. 5). Therefore, the maximum room temperature wall stress observed for the prototype FISH bed at high hydrogen loadings is <40% of the ASME Code allowable limit. This result is consistent with that obtained from SB01 testing, where a maximum wall stress of ~38 MPa at an H/M>0.80 (~35% of the ASME limit) was obtained.[2]

These results verify that the added design features of the FISH bed may actually reduce PV wall stresses, particularly because the stresses in section G, proximate to the internal divider plates, are similar in magnitude to those in sections E and F. Additionally, previous wall stress studies on hydride beds without heat transfer foam have shown maximum tensile stresses occur at the equator of the vessel, where the cross-section becomes completely occupied by the hydride material, with minimal compressive stress observed along the top of the bed where the void space is located.[2,3] The inset of Figure 2a shows a map of the maximum hoop stress distribution along the FISH bed, indicating that the more evenly dispersed hydride material in the heat transfer foam may contribute to a more uniform wall stress distribution.

Because the absolute wall stress is calculated as an accumulation of the changes in strain response at each desorption step, any strain/stress calculation error is more significant at the lower H/M values where strain gage output is very small and strongly influenced by temperature and pressure variations. This is evident in the variation between compressive and tensile stress for some of the gages (e.g., DH1 and GH3 in Figure 2a) below 0.30-0.50 H/M. Therefore, to obtain a more accurate depiction of the wall stresses at low bed loadings, a stepwise protium absorption was performed. Figure 2b shows the variation of the hoop stress as the hydride bed loading was incrementally increased from 0 to 0.77 H/M.

The location of the maximum stress for a given H/M was found to be dependent on whether the bed is being absorbed or desorbed. This dependency may be attributed to the difference in the initial gas loading and unloading locations within the bed. The gas is loaded through the porous metal tube located toward one end of the bed; thus, gas absorption would first occur near the porous tube, resulting in higher absorbed gas concentration proximate to the porous tube for a partially filled bed. Upon unloading, the gas is desorbed more uniformly as a result of the full-bed-length electric heaters, although some asymmetry likely exists as a result of the heater location relative to the gas loading tube and the absorbed gas concentration variation. Other factors, including the distribution of the hydride material within the foam void volume and any external vessel constraints, may also contribute to different distributions of stress during loading and unloading processes.

Another important observation from Figure 2 is that all of the gages show a rapid reduction in stress upon small incremental desorption. For example, the gages exhibiting the largest stress at maximum loading, GH1 and FH3, experienced 80% and 60% reduction in stress, respectively, in the first desorption step from 0.77 to 0.71 H/M. The stresses at all of the gage locations continued to decrease with further unloading and were completely relieved (within a gage accuracy of ±4 MPa) upon reaching H/M~0.65-0.60. However, a more gradual increase in the wall stress was observed during incremental absorption, with an initial gage response to loading in the 0.30-0.45 H/M range. This hysteretic behavior of the strain gage response is typical and has been previously reported.[2,3] This effect is most pronounced in the strain gages exhibiting the largest stress, e.g., the wall stress hysteresis observed for GH1 is shown in Figure 3. The differences in the initial gas absorption/desorption mechanisms, as discussed above, may also contribute to the observed hysteresis in the strain response for an individual gage.

Lastly, the wall stress variation with H/M reveals that minimal PV wall stress is expected in the ideal operating range of LANA.85, which is typically within the H/M range of 0.10 to 0.55 where minimal changes in equilibrium pressure occur over large changes in hydride loading (plateau region). Furthermore, even at the extremes of the LANA.85 isotherm (α and β phases), the maximum observed wall stresses remain well below ASME Code limits.

IV. CONCLUSIONS

The hydriding-induced wall stress evaluation of the prototype FISH bed presented herein provides several important conclusions regarding the bed design verification.

1) Advanced design features of the prototype FISH bed do not result in additional strain on PV walls

2) Maximum tensile wall stress measured at high hydrogen loading (H/M=0.77) is <40% of ASME allowable limit

3) Spatial variation in the location of gas absorption and desorption due to loading tube design and heater position result in different distributions of wall stress for the same H/M.

4) Typical hysteresis of the strain gage response upon gas loading and unloading was observed

5) Negligible hydriding-induced wall stress is expected within the normal H/M operating range for LANA.85.

The results described herein confirm those obtained for the SB01 bed and were consistent with those previously reported for similar hydride storage beds without the advanced features. Completion of this evaluation marks a major milestone in the design and performance verification of the FISH bed for tritium service.

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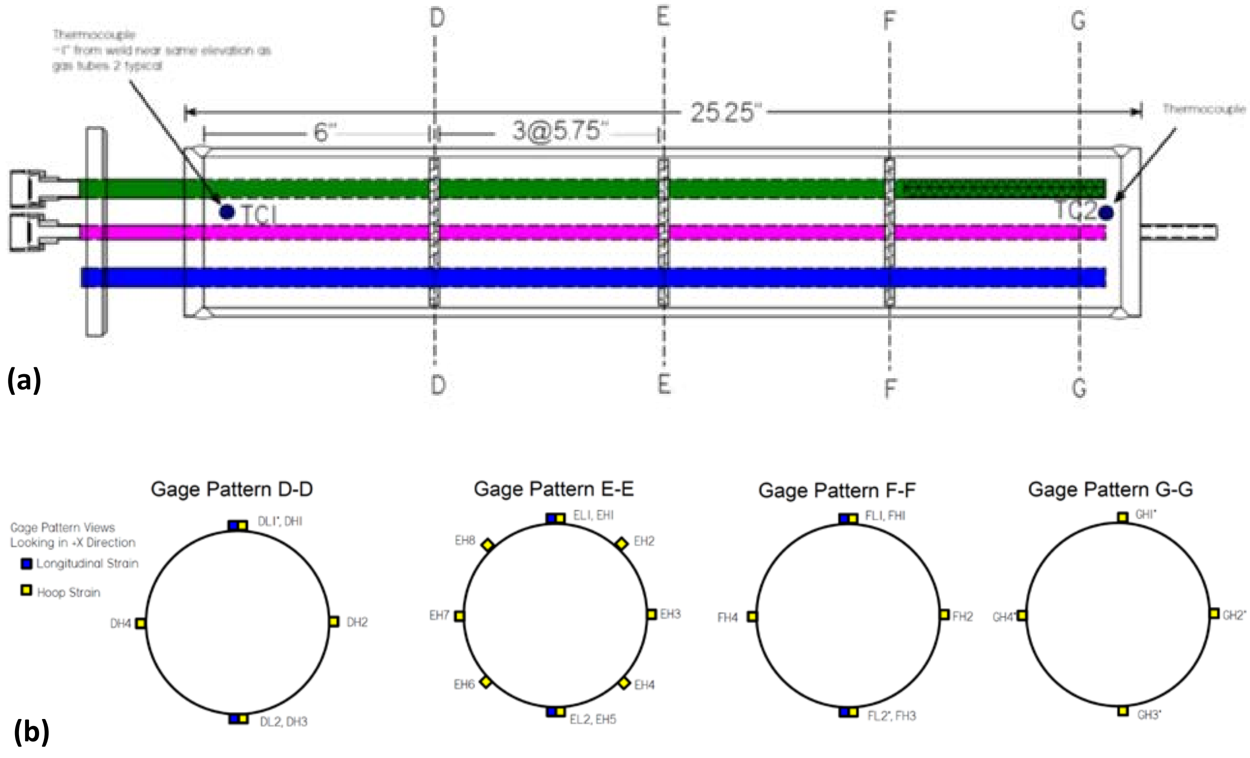

Figure 1. (a) Strain gage layout on the prototype FISH bed. (b) Gage pattern as viewed from nozzle end.

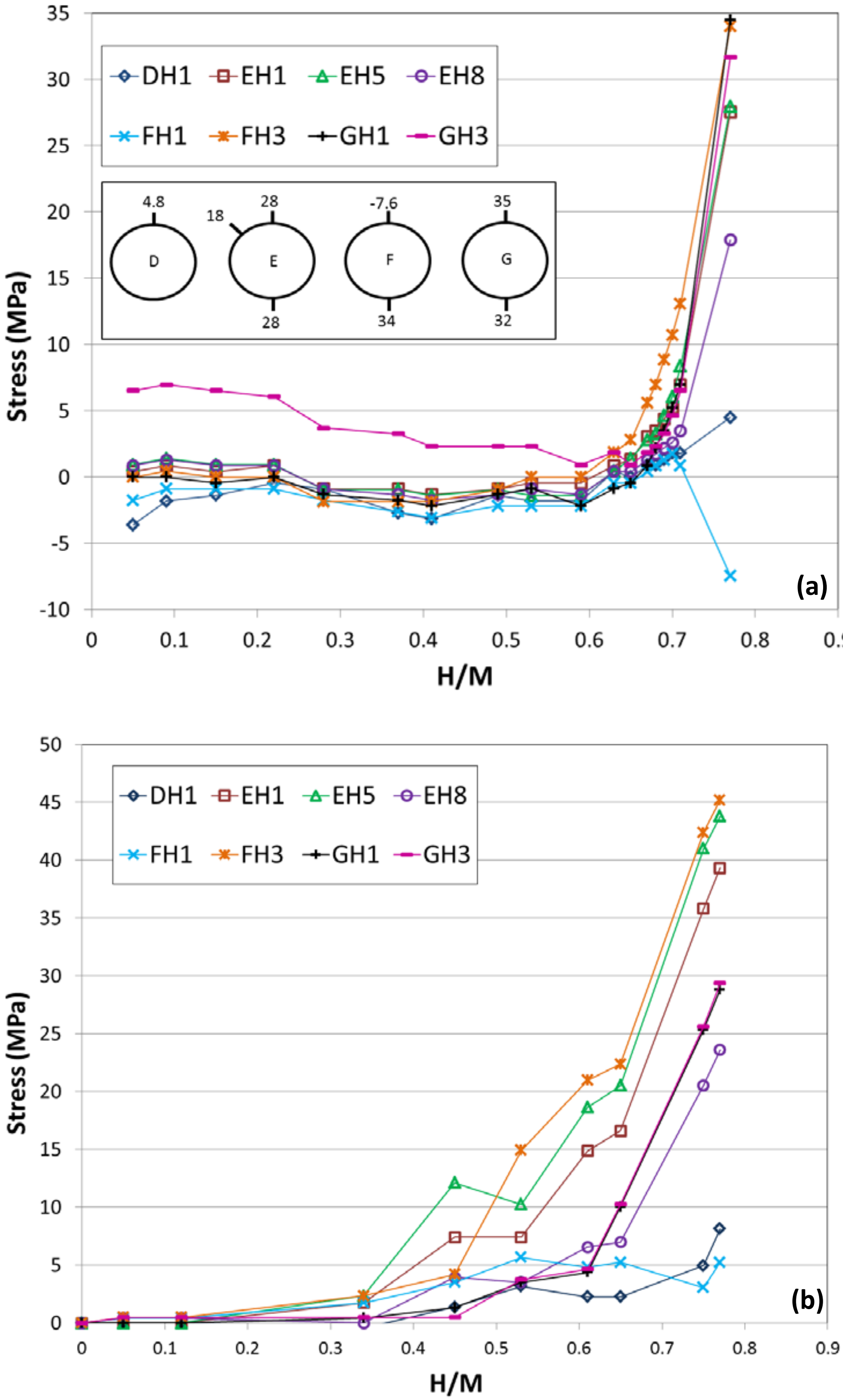

Figure 2. Hoop stress variations with H/M during protium (a) desorption (max hoop stress map shown in inset) and (b) absorption.

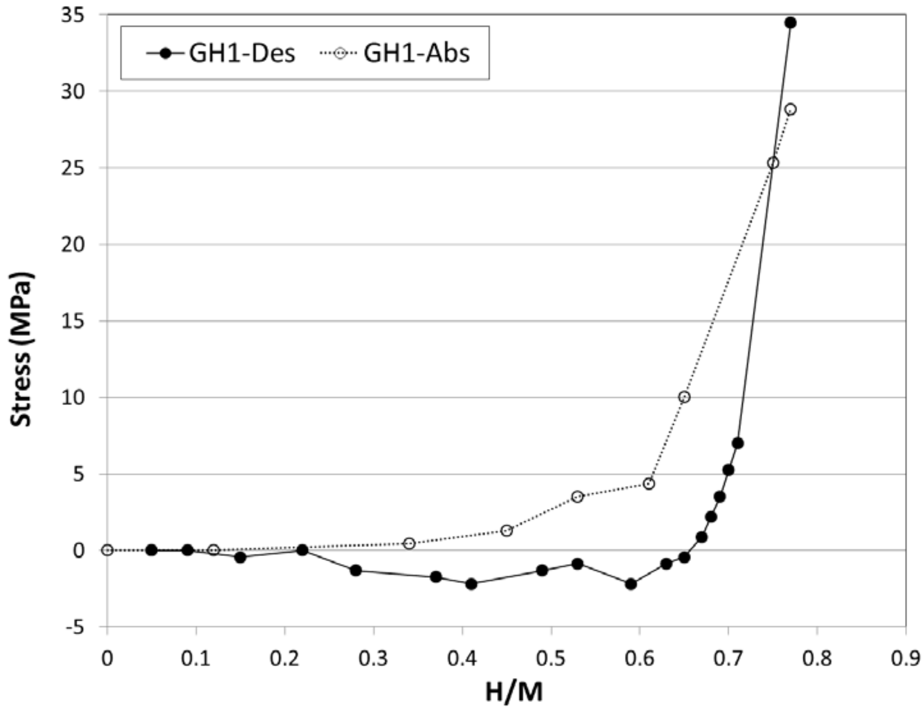

Figure 3. Typical strain gage hysteresis (shown here for GH1) during protium absorption (open circles) and desorption (closed circles).

Figure Captions:

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