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Induction Heating for Tritium Storage Beds

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PREFACE

The work described herein was performed to satisfy Gas Processing Area of Interest # 3: "Develop methods to deploy alternate ways to heat existing process equipment to minimize impact to glovebox environment” from the 2018 PDRD Call for Proposal STRE Process Support Document.

EXECUTIVE SUMMARY

Metal hydride beds used for storing hydrogen isotopes accumulate helium due to beta-decay of tritium. Helium alters the hydrogen capacity and plateau pressures of these storage beds and ultimately results in the beds being disqualified for use in tritium facilities. Removal of helium and hydrogen isotopes for disposal or storage bed regeneration can be achieved with sufficient heating; however, existing Gen 1 and Gen 2 storage beds are not designed to reach helium removal temperatures and face disposal challenges. In this report, we describe experiments and Multiphysics models that were used to develop a method to achieve induction heating of existing tritium storage beds using induction coils placed on the outside of the beds. The heating method involves low-frequency (< 100 Hz) induction heating through flexible solenoid coils that wrap tightly around the outer jacket of a tritium storage bed. This method of heating offers a pragmatic path to heat existing storage beds for metal hydride regeneration, helium removal for disposal, and possibly routine gas cycling operations.

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LIST OF ABBREVIATIONS

AC	Alternating Current
IR	Infrared
LANA75	$LaNi_{4.25}Al_{0.75}$
OD	Outer Diameter
PDRD	Plant Directed Research Development
SRNL	Savannah River National Laboratory
SRS	Savannah River Site

1.0 Introduction

Metal hydride beds used for storing hydrogen isotopes at the Savannah River Site (SRS) are heated and cooled to desorb and absorb gases. Two storage bed configurations have been utilized by SRS Tritium. Gen 2 Beds achieve heating through electric cartridge heaters positioned laterally along the longest axis of the storage bed. Gen 1 beds achieve heating and cooling through hot and cold nitrogen flow. While these beds/heating configurations are well-designed for gas cycling operations, it is unclear if they can be regenerated to starting conditions once too much helium has accumulated in them from tritium beta-decay. Complete helium removal from metal hydride beds occurs at high temperatures that cannot be reached by beds currently in service. Thus, existing Gen 1 and Gen 2 beds need to be heated through an alternative method to remove helium so the beds can either return to normal operation or be disposed of. In this report, we describe experimental and computational modeling efforts through the Plant Directed Research & Development (PDRD) program that were aimed at determining if induction heating can be used to heat metal hydride storage beds in a practical manner in order to achieve helium removal and hydride regeneration.

In the first year of this two-year PDRD, we executed tasks aimed at understanding how individual components in Gen 1 and Gen 2 beds heat and cool in an induction field. Our results showed that all primary components in these storage beds (outer jacket, inner process vessel, aluminum foam, and LANA75) experience rapid and controllable heating when exposed to a magnetic field emanating from an induction coil. At high and middle alternating current (AC) frequencies (i.e. the frequency of the AC current flowing through an induction coil) , most of the induction heating occurs on the surface closest to the induction coils (i.e. the outer jacket surface of a storage bed). In year two of this PDRD, we focused on developing induction heating methods that would allow for controlled heating inside of existing storage beds using induction coils placed on the outer jacket of a bed. We uncovered a pragmatic path to heat existing storage beds for regeneration, helium heel removal, and possibly routine gas cycling operations by using low-frequency (< 100 Hz) induction heating through flexible solenoid coils that wrap tightly around existing storage beds and their protruding components. Details of these two years of experimental and computational work are described herein.

2.0 Experimental Procedure

Induction Heating

A 7.5 kW, 200 KHz Lepel induction power supply was used for all induction heating experiments. This instrument uses a programmable digital control panel for setting power and time during heating operations. Typical heating experiments of storage bed components used 300 W (~4% power) of 55 kHz alternating current (AC).

Temperature during induction heating experiments was monitored using a FLIR SC645 model infrared (IR) camera capable of measuring a temperature range of -20 ℃ to 2000 ℃ with an accuracy of ±2°C of the actual temperature. The camera had a 24.6 mm focal length, 0.69 mrad spatial resolution, a spectral range of 7.5 - 14 µm, and was mounted at the top and side of the induction power supply in order to safely observe heating.

Computational Modelling

Finite element models were created using COMSOL Multiphysics version 5.2. 2D axisymmetric models were generated to couple the AC/DC and Heat Transfer modules to accurately simulate induction heating. These models allow users to simulate storage bed heating and cooling under a variety of induction heating conditions that cannot be manipulated experimentally (e.g. induction frequency, thickness of bed components, composition of bed components, etc.).

3.0 Results and Discussion

Experimental Induction Heating

In the first year of this PDRD, we experimentally evaluated the induction heating properties of the individual components of Gen 1 and Gen 2 tritium storage beds. These components include the 304/304L outer jacket, the 304/304L process vessel, aluminum foam, and LANA75. For clarity, a generalized diagram of a Gen 2 tritium storage bed is shown in Figure 3-1.

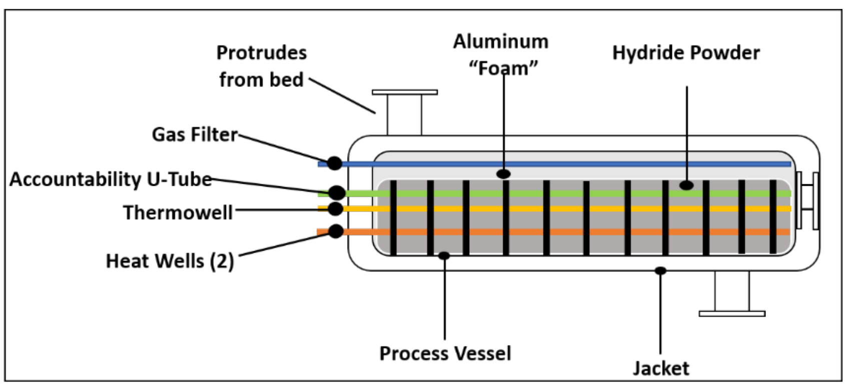

Figure 3-1. General schematic of a Gen 2 storage bed.

During heating experiments, an induction solenoid coil was wrapped closely around the outside of our heated workpiece. We adjusted several parameters in our heating experiments including induction power, heating time, and thickness of the outer jacket and process vessel. The temperature of the individual bed components was monitored in real-time using an IR camera. Experimental setup and thermal profiles of the different components are shown in Figures 3.2 – 3.6. As can be seen in these figures, induction heating of the individual components of both Gen 1 and Gen 2 storage beds is very fast, even at low power. This result highlights the speed and energy-efficiency that is obtained with induction heating. The red spot on the aluminum in Figure 3.4 is a reflection from a nearby digital display.

Due to high electrical conductivity, aluminum foam was found to experience the slowest heating of all storage bed components. These results are important because they show that induction heating can be used to heat each component in a storage bed with no material modifications needed. Further, these results highlight the speed and energy-efficiency that can be achieved when using induction heating.

Figure 3-2. A copper induction coil is shown during heating of a 6” long, schedule 10, 4” OD, 304/304L stainless steel cylinder. Except for the short length, the dimensions and composition of this cylinder are the same as the outer jacket used in both Gen 1 and Gen 2 storage beds.

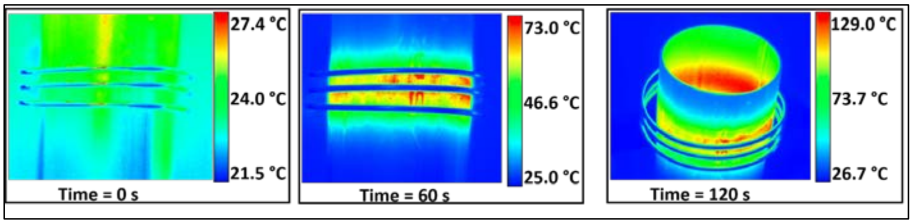

Figure 3-3. Infrared radiometry was used to monitor the heating of the cylinder from Figure 3-2. The cylinder experiences rapid heating from an induction coil operating at 300 W power and 55 kHz ac frequency. The heating is not perfectly uniform due to asymmetry in the induction coil.

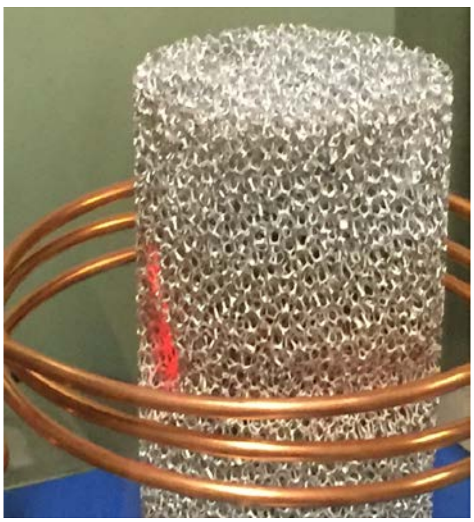

Figure 3-4. An induction coil is shown during heating of aluminum heat transfer foam.

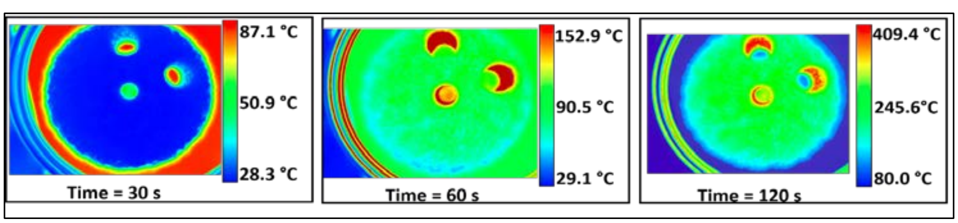

Figure 3-5. Infrared radiometry was used to monitor the heating of the aluminum foam shown in figure 3-4. The foam experiences rapid heating in an induction field. Holes in the foam designated for a thermocouple and heater cartridges appeared to get hotter than contiguous portions.

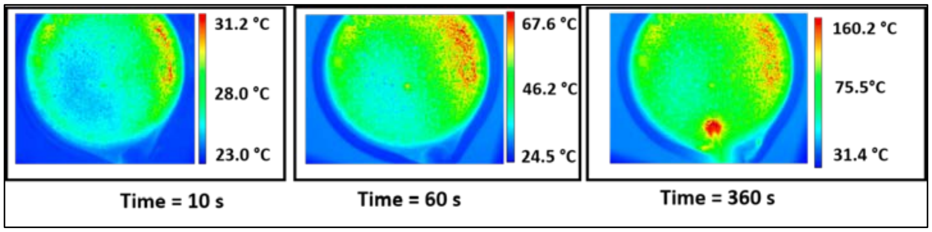

Figure 3-6. Infrared radiometry images of LANA75 experiencing induction heating at 300 W and 55 kHz AC frequency. The heating is not perfectly uniform due to asymmetry in the induction coil. A thermocouple was placed in the LANA during this experiment to verify temperature with the IR image but the metal thermocouple experience induction heating that rendered its temperature measurements inaccurate

The thermal profile of inductively heated storage bed components was also measured when the components were combined to form a skeletal structure of a storage bed (Figure 3-7). The induction heating properties were measured at each stage of the assembly. Figure 3-8 shows the heating profile of the combined outer jacket and process vessel. In all experiments involving the combination of storage bed components, induction heating was found to only occur at the surface of the outer jacket. This surface heating - known as the “skin effect” - manifests at both high and middle AC frequencies.

The skin effect is an important caveat when considering induction to heat existing tritium storage beds. Thermal gradients are inherent in an imperfectly insulated system like a storage bed inside a glovebox. For the center of a tritium storage bed to reach temperatures high enough to removal the helium heel it would be necessary to heat storage bed surfaces above these temperatures due to inherent gradients that would exist from the surface to the center of a storage bed. Unfortunately, in tritium applications, any heating above design temperatures can generate a non-conformance report. that could disqualify a storage bed from being used for future tritium operations. Therefore, high and middle AC frequency induction heating of existing tritium storage beds – using coils placed on the outside of the bed- are unlikely to be useful for hydride bed regeneration, but could be useful for end-of-life heel removal and bed disposal.

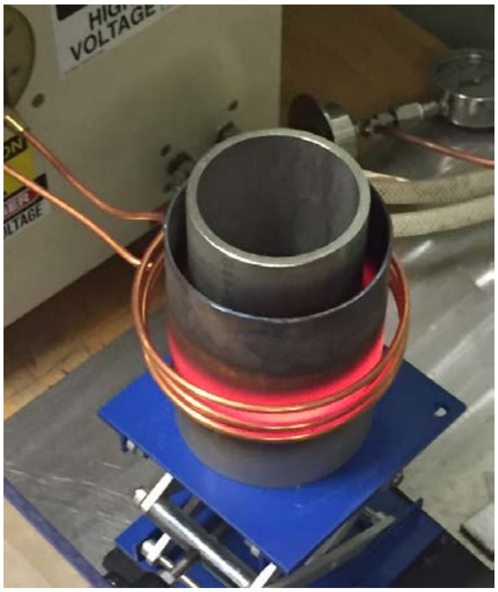

Figure 3-7. Induction heating is performed on a schedule 40, 3" OD, 304/304L stainless steel cylinder inside of a schedule 10, 4" OD, 304/304L stainless steel cylinder. This configuration of cylinders mimics the configuration used in Gen 2 tritium storage beds. Notice the incandescence of the outer jacket as it is heated above 500 ℃, yet the process vessel does not experience any direct induction heating.

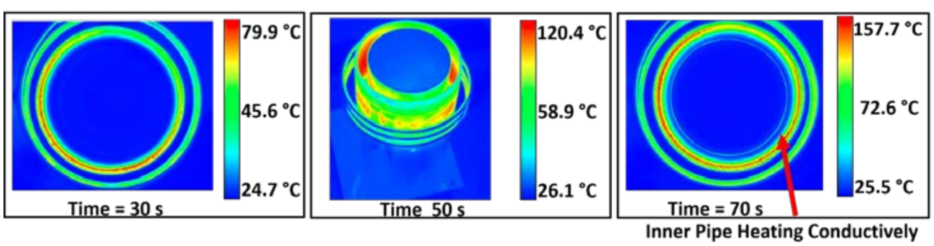

Figure 3-8. Infrared radiometry reveals the heating profile for the cylinders shown in figure 3-7. The outer cylinder experiences all the induction heating. The inner cylinder only heats due to conductive heating from the outer cylinder.

Computational Studies for Targeted Internal Heating

Concurrent with our heating experiments, we developed a COMSOL Multiphysics model to simulate heating of a Gen 2 storage bed. Figure 3-9 shows a simplified version of our simulated storage bed. Our simulations were developed so we could adjust parameters that could not be experimentally adjusted, like induction frequency and the composition of various components to these storage beds. The goal was to determine if a certain combination of induction heating parameters could be used to overcome the skin-effect caveat that was discovered in our experiments.

Multiple simulations confirmed our experimental findings that induction heating occurs almost entirely at the metal surface closest to the induction coil when using high (~100 kHZ – 450 kHz) and middle AC frequencies (~ 2 MHz – 100 kHz) [1] (Figure 3-10). Again, while this surface heating might be useful for end-of-life helium removal, it would likely not be useful for metal hydride regeneration.

With corroborating experimental and computational data, we concluded after our first-year efforts (FY18) that induction heating is a fast and energy-efficient way to heat existing tritium storage beds; however, high and middle AC frequency heating can only generate heat at the metal surface that is closest to the induction coils.

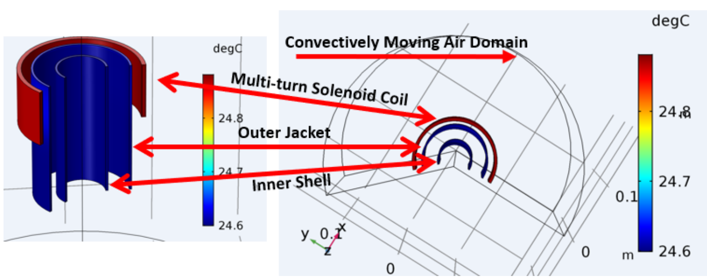

Figure 3-9. A COMSOL Multiphysics model was developed to simulate induction heating of a simplified Gen 2 storage bed.

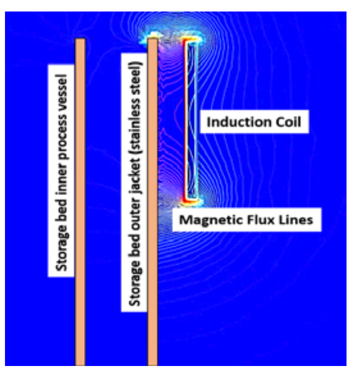

Figure 3-10. COMSOL simulation showing magnetic flux lines emanating from an induction coil. The concentric flux lines concentrate entirely on the storage bed outer jacket and make no direct contact with the inner process vessel.

In year two of this PDRD, we continued our COMSOL simulation efforts aimed at finding a set of induction heating parameters that could be used to generate internal induction heating of existing Gen 1 and Gen 2 storage beds.

After rigorous refinement to our FY18 model, we performed detailed simulations of induction heating over a swath of AC frequencies. In each simulation, the average temperature was recorded at the center of the simulated storage bed (i.e. the LANA and aluminum foam component of the bed). We found that surface heating dominates all thermal profiles until significantly low AC frequency is employed. Specifically, AC induction frequencies ≤ 100 Hz generate heat almost exclusively at the center of a storage bed. Thus, the penetration depth (i.e. the depth electromagnetic radiation can penetrate a material) of induction fields increases with decreasing AC frequency. The magnetic flux lines from a simulation at 80 Hz illustrate this point and are shown in Figure 3-11.

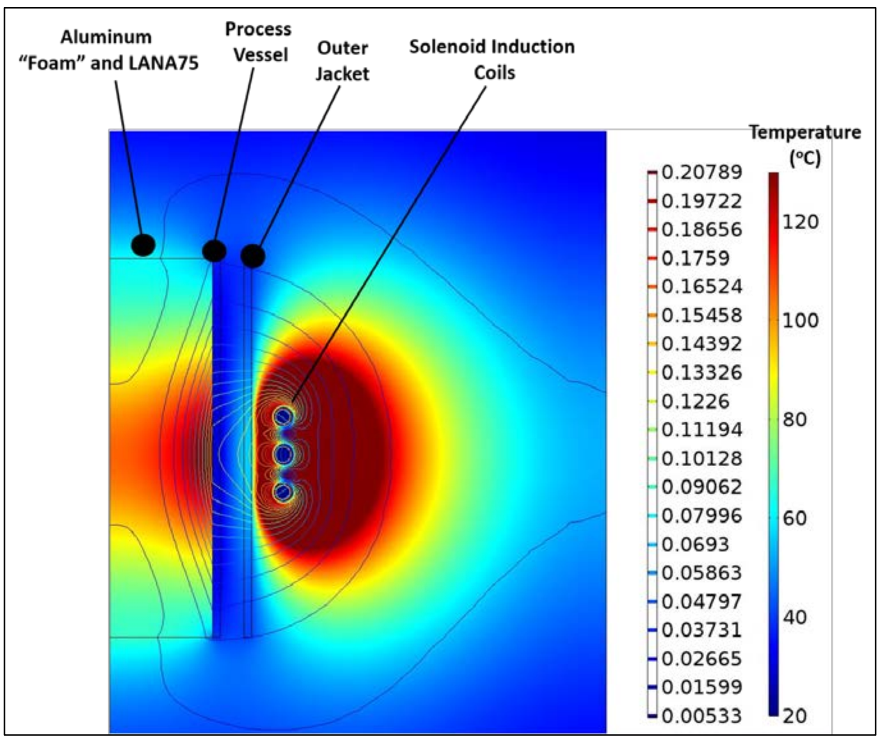

Figure 3-11. Cross-section of a simulated Gen 2 bed being heated at 80 Hz AC induction frequency. Note that most of the heating occurs near the center of the process vessel. Heat at the outer jacket is due to conductive heat transfer from the surroundings. The heating of air near the induction coils is an artifact of our model. Specifically, heat transfer from cooling water inside the coils to the copper coils was not built into the model even though it would be present in a real setting. While this modeling artifact has no impact on the results regarding the LANA75/foam heating, more accurate heat exchange could be used to improve this model in the future.

The discovery that low frequency induction can be used to deliver controlled heating inside of existing storage beds using induction coils placed on the outside of the beds is significant. We believe this form of heating is a pragmatic way to heat existing storage beds for hydride regeneration and helium removal. This type of heating should have minimal impact on the glovebox environment and should prevent stainless steel components from getting too hot.

To determine how long a full-scale Gen 2 bed would need to be heated to reach various processing and regeneration temperatures, we performed rigorous simulations of induction heating at 80 Hz using a variety of induction powers. These simulations showed that hydride regeneration temperatures can be reached in under an hour using an induction power of ≥ 20 kW. These results are displayed in Figure 3-12 and they represent non-insulated heating conditions (i.e. the simulated storage bed could freely exchange heat with its surrounding environment).

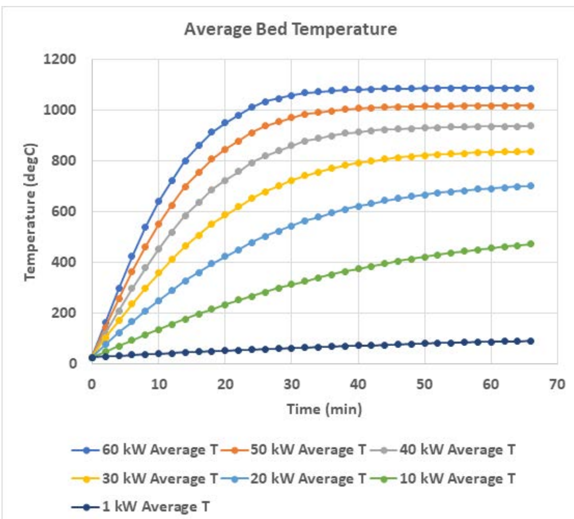

Figure 3-12. Average temperatures of the center of a full-scale storage bed were modelled and are plotted as a function of time and various induction powers. The employed induction frequency was 80 Hz. Steady-state temperatures are reached within 40 – 60 minutes for all power levels.

Unfortunately, low-frequency induction power supplies are not commonplace. Thus, we have been unable to experimentally validate our computational findings. However, as stated above, we have performed numerous preliminary experiments at higher frequencies and have rigorously modelled our low-frequency approach using Multiphysics software. We have also worked with several vendors to determine if a low-frequency power supply could be developed to mimic our computational results. After some searching, the engineering team at Inductotherm Corp. ran independent evaluations and simulations based on generalized information that was provided to them, and they deemed it feasible to build a power supply to meet the criteria outlined in our simulations. Their 50-kW instrument can deliver AC frequencies of 60 – 100 Hz and has been quoted at $100 k.

Following our discovery that low frequency AC frequencies can be used to heat existing tritium storage beds in a practical manner, we sought to determine the best method for placing induction coils around existing storage beds. This is a challenge because typical induction coils are made of thick, semi-rigid metals like copper tubes that are typically pre-molded for a specific workpiece. [2] A major problem with using a rigid coil to heat existing storage beds is that most beds contain at least one component that protrudes from the bed; thus, rigid coils would need to be oversized to fit these protruding components, which would result in poor coupling between the coil and the workpiece.

In an effort to circumvent this issue, we purchased a flexible induction coil that can be molded around protruding components. The flexible coil is composed of multiple, small flexible copper wires that are encased in a flexible polymer tube. The ends of the tube are joined to a copper adapter that can be fixed to an induction power supply. The utility of this coil was rigorously tested using high-frequency induction heating experiments on metal cylinders. Figure 3-13 shows our experimental setup for testing the flexible coil. In our tests, the coil was found to operate similarly to a rigid copper coil. The flexible coil took only a few minutes to set up and disassemble in our cylinder heating experiments.

Figure 3-13. Left: Stock photo of a flexible induction coil that can be used to quickly set up a workpiece for induction heating. Image courtesy of Ambrell.com. Right: A typical induction heating experiment using the flexible coil to heat a metal cylinder workpiece. Fiberglass insulation is placed between the cylinder and the induction coil to protect the coil from the heat of the metal.

A general important advantage of using induction coils for heating is that the area of heated material is very high since the coil can wrap around the entire outer surface of a heated workpiece. With such high coverage by the coil, temperature gradients are expected to be minimal when using induction heating. Additionally, the coil can be wound around specific components of the bed to protect lower temperature rated components in the bed from overheating. The estimated heated surface area for currently used cartridge heaters in Gen 2 beds is ~ 170 in^2. Depending on the number of induction coil windings, heated surface areas around 600 in^2 could be reached for existing storage beds, thereby allowing for more rapid and uniform heating. Further, because heating occurs without physical contact between the material being heated and the induction coil, beds should experience faster cool-down times.

4.0 Conclusions

Experimental and computational modeling efforts have resulted in the discovery of a pragmatic method to heat existing Gen 1 and Gen 2 storage beds for helium heel removal and hydride regeneration. This work satisfies the goal of Gas Processing Area of Interest # 3: "Develop methods to deploy alternate ways to heat existing process equipment to minimize impact to glovebox environment", in the 2018 PDRD Call for Proposal STRE Process Support Document. [3]

Induction heating can be delivered to the center of existing storage beds – where LANA and heat-transfer foam reside – by using very low AC induction frequencies. At frequencies <100 Hz, the penetration depth of the induction heating is significantly increased. Thus, induction coils placed on the outside of a tritium storage vessel can be used to deliver significant heat to the center. This form of targeted heating should prevent any components in a storage bed from exceeding design temperatures, which would disqualify them for use in tritium operations. Furthermore, because induction heating is so rapid, and the heat source (the coils) is not actually hot, the central components of a storage bed can be heated and cooled very quickly, thus limiting potential material changes that can occur due to prolonged heating at high temperatures.

Existing hydrogen beds are irregularly shaped and contain protruding components that might be difficult to set up for induction heating using rigid induction coils. However, flexible induction coils, like the ones described herein, should be able to heat existing storage beds with minimal setup time. Because a flexible coil can wrap around existing components, it should be able to couple as closely as possible to heated workpieces, thus maximizing energy transfer.

In summary, induction heating of the components in Gen 1 and Gen 2 storage beds is both rapid and energy efficient. The technique has large utility and can be performed using flexible coils operating at a specific frequency to deliver induction heat at a specific location within a complex component thereby allowing for a variety of applications. In two years, our PDRD has progressed from feasibility determination to technology development; we have submitted an invention disclosure that details our progress.

5.0 Recommendations, Path Forward or Future Work

Future work should focus on evaluating site-specific heating of a storage bed using a low frequency induction heating system with a flexible induction coil that can be easily tailored to fit complex geometries in a prototypical application environment.

A suggested timeline of future work is provided below

1) Procure and install a low-frequency induction power supply (20– 24 weeks)
2) Perform preliminary testing and diagnostics on low-frequency instrument (6 – 12 weeks)
    - Tests will include heating experiments using infrared radiometry to evaluate heating of simplified storage bed components (i.e. stainless-steel pipes assembled in a similar configuration to a storage bed but without welds)
3) Perform heating tests using a full-scale storage bed (6 – 12 weeks)

6.0 References

[1] V. Rudnev, D. Loveless and R. L. Cook, Handbook of Induction Heating, Boca Raton, FL: CRC Press, 2017.

[2] S. Zinn and S. L. Semiatin, "Coil Design and Fabrication: Basic Design and Modifications," *Heat Treating,* pp. 32-41, 1988.

[3] M. A. Collins, "Call for Pre-Proposals: Savannah River Tritium Enterprise Plant Directed Research Development and Demonstration (PDRD) Program for FY18 (U)," SRNS-T0000-2017-00116.

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