Measurement of Hydrogen Purge Rates in Parabolic Trough Receiver Tubes

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MEASUREMENT OF HYDROGEN PURGE RATES IN PARABOLIC TROUGH RECEIVER TUBES

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Abstract

The purpose of this research is to investigate and develop methods to remove hydrogen centrally from commercial parabolic trough power plants. A mathematical model was developed that tracks the generation and transport of hydrogen within an operating plant. Modeling results predicted the steady-state partial pressure of hydrogen within the receiver annuli to be ~1 torr. This result agrees with measured values for the hydrogen partial pressure. The model also predicted the rate at which hydrogen must be actively removed from the expansion tank to reduce the partial pressure of hydrogen within the receiver annuli to less than 0.001 torr. Based on these results, mitigation strategies implemented at operating parabolic trough power plants can reduce hydrogen partial pressure to acceptable levels. Transient modeling predicted the time required to reduce the hydrogen partial pressures within receiver annuli to acceptable levels. The times were estimated as a function of bellows temperature, getter quantity, and getter temperature. This work also includes an experimental effort that will determine the time required to purge hydrogen from a receiver annulus with no getter.

Keywords: parabolic trough, modeling, hydrogen, decomposition, permeation

1. Introduction

Parabolic trough power plants offer an attractive option for near-term, utility-scale, dispatchable, renewable electricity generation. More than 500 MW of capacity currently are in place in the United States and Spain, with many new installations planned for the next five years [1,2]. Key benefits of parabolic trough power plants are their reliable design and proven commercial performance. Essentially all of the currently operating plants use a heat-transfer fluid (HTF) that is a eutectic mixture of two organic compounds, biphenyl and diphenyl oxide. At elevated temperatures up to 393ºC, the organic components undergo very slow degradation reactions that produce hydrogen as a byproduct [3]. Hydrogen is transported by the HTF to many components within the power plant. Hydrogen that permeates through the receiver tube walls establishes an equilibrium partial pressure within the vacuum annuli of the receivers. Within the receiver annulus, the equilibrium partial pressure balances the net permeation rate into the annular volume from the receiver tube with the permeation rate out of the annular volume to ambient air. Permeation out of the annular volume occurs primarily through the metal bellows, which seal the receiver tube to the enclosing glass tube. Hydrogen within the annular volumes of the receivers may result in substantial degradation of the thermal performance of the receivers. This work is investigating methods to eliminate hydrogen from the receivers of a parabolic trough power plant by removing it from a central location within the plant.

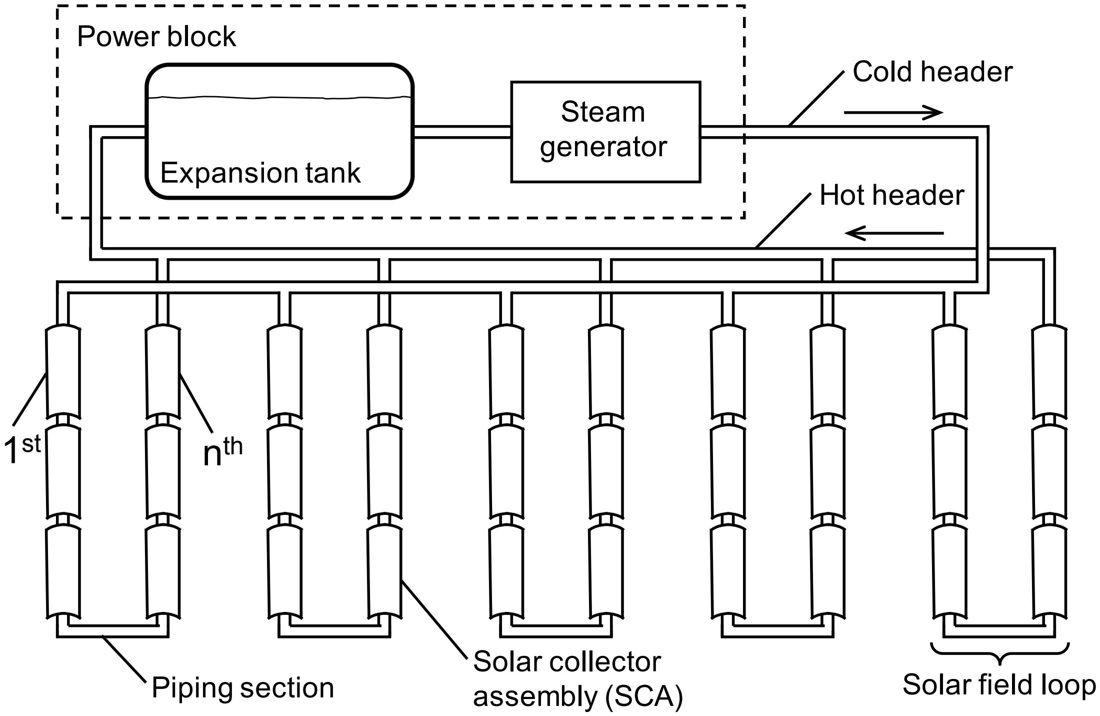

Figure 1. Schematic of parabolic trough power plant.

The HTF within a power plant flows through several parallel loops that comprise the solar collector field (Fig. 1). Each loop consists of multiple solar collector assemblies (SCAs), which include the parabolic reflector, receiver, and accompanying support structure. Piping sections connect the SCAs within each loop. A header supplies HTF from the plant power block to the SCA loops. A second header returns HTF to the power block from the loops. Components within the power block that contain HTF are the steam generator and expansion tank. HTF flows from the power block to the solar collector field and back to form a closed loop.

The HTF that is currently used in essentially all of the operating plants is a eutectic mixture of two organic compounds, biphenyl oxide and diphenyl ether. The fluid is thermally stable to a maximum temperature of 390ºC. Its vapor pressure at 393ºC is about 10 atmospheres, and its freezing point is 12ºC. These thermal properties allow parabolic trough power plants to operate within a temperature range of 293º–393ºC. Its low freezing point minimizes the risk of freezing in the solar collector field when the plant is off-sun.

Alternate HTFs with higher operating temperatures are being considered for use in future power plants [4]. These fluids will generate higher-temperature steam and will allow the turbine and plant to operate with greater thermodynamic efficiencies. Molten nitrate salt mixtures offer higher operating temperatures with low vapor pressure, but their freezing points are typically too high to prevent freezing during off-sun periods. Because there is currently no demonstrated alternative HTF, near-term installations are being designed to operate with the organic eutectic.

At temperatures near 393ºC, the organic components undergo a variety of degradation reactions. These reactions include ring closure of the ether linkage in diphenyl oxide and free-radical polymerization of biphenyl to form products with higher molecular weight. Both reactions produce hydrogen as a byproduct. The hydrogen is transported throughout the power plant to all components that contain HTF. Its high permeability in metals allows it to permeate through the steel walls of the expansion tank (Fig. 2), steam

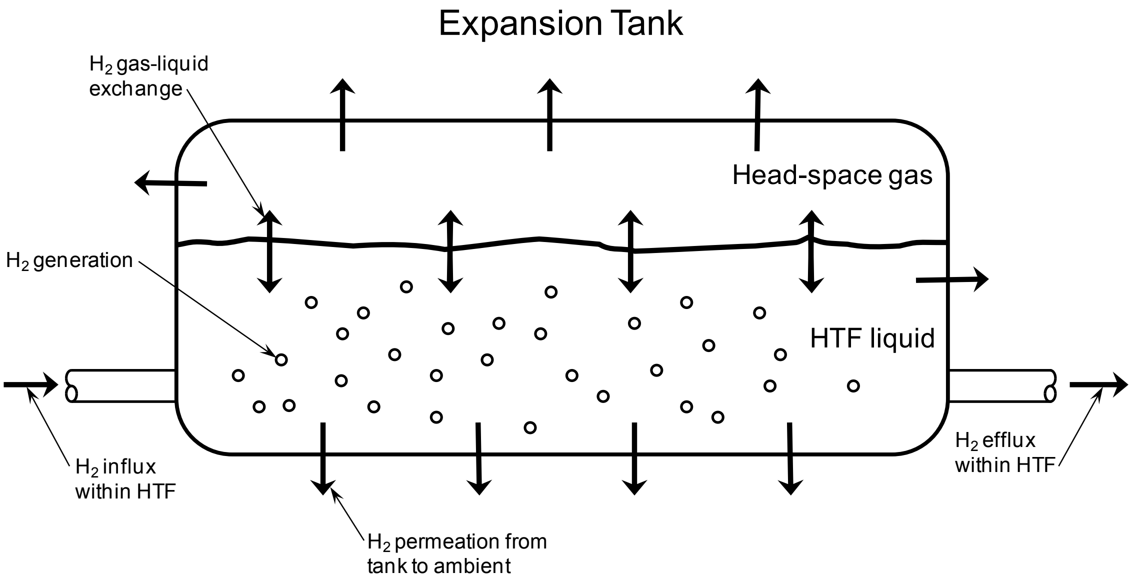

Figure 2. Hydrogen generation and transport in the HTF expansion tank.

generator, piping, and receiver tubes. Hydrogen that permeates through the receiver-tube walls establishes an equilibrium partial pressure within the annular volumes of the receivers (Fig. 3).

The equilibrium partial pressure balances the net permeation rate into the annular volume from the receiver tube with the permeation rate out of the annular volume to ambient air. Permeation out of the annular volume occurs primarily through the metal bellows, which seal the receiver tube to the enclosing glass tube. All of the hydrogen ultimately passes from the plant to ambient air.

The occurrence of hydrogen within the annular volumes of the receivers may result in substantial degradation of their thermal performance. Decreased thermal performance (Fig. 4) is caused by the relatively high thermal conductivity of hydrogen at low partial pressures of about 1 torr [5]. Receivers that contain hydrogen in their annular volumes retain less of the absorbed thermal energy than those without hydrogen. They operate with lower thermal efficiency and cause a decrease in the overall plant efficiency. The resulting decrease in power output from the plant can be substantial. Current receivers contain getter materials that absorb hydrogen within the annulus. New receivers contain getters with more capacity to absorb hydrogen and maintain vacuum for many years. A method that removes hydrogen from a central location in the power plant would complement the receiver getters.

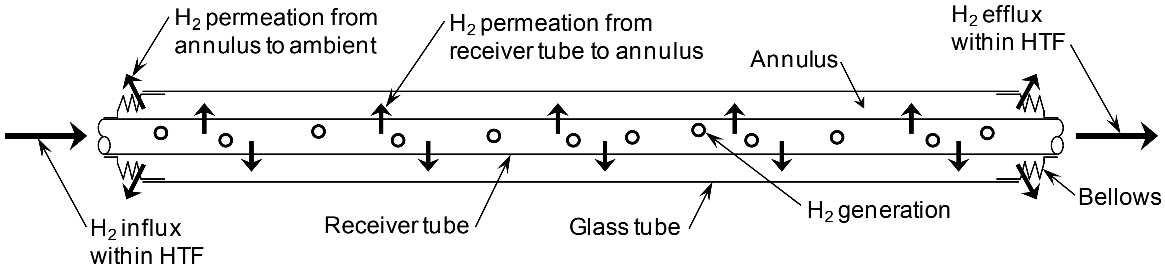

Figure 3. Hydrogen generation and transport within the receiver.

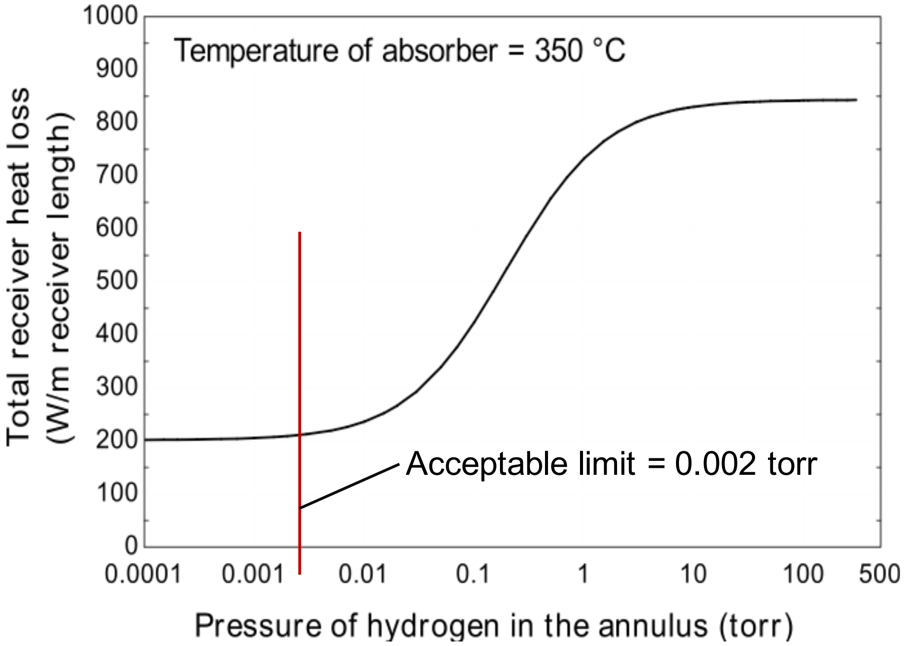

Figure 4. Receiver heat loss as a function of hydrogen partial pressure.

2. Objective

The objectives for this work were to determine the rate at which hydrogen diffuses out of a receiver annulus as a function of receiver tube and bellows temperatures and compare results to the model predictions.

3. Approach

Previous work modeled hydrogen generation and transport within a parabolic trough power plant. Modeling was accomplished using a steady-state hydrogen material balance on the components of the power plant that contain HTF. Several mechanisms for hydrogen generation and transport were included in the model. Hydrogen (H_2) is initially contained in the HTF and is generated by the thermal decomposition of the HTF components. Therefore, transport of hydrogen within the plant occurs via the normal flow of HTF between the plant power block and the solar collector field. In addition, permeation through the walls of the expansion vessel, steam generator, piping, headers, and receivers results in transport of hydrogen out of the plant to ambient air. At steady state, the model predicted a hydrogen partial pressure of 1 torr in the receiver annuli when hydrogen is present in the plant HTF. Steady-state modeling results showed that if the HTF within the expansion tank of the plant is kept free of hydrogen, then the HTF that is in circulation within the solar collector field will also remain free of hydrogen. This result is due primarily to the fact that the time required to generate significant concentrations of hydrogen in the HTF is much greater than the time required to circulate HTF from the expansion tank to the collector field and back again. Under these conditions, the model predicted that the steady-state partial pressure of hydrogen in the annuli of the receivers will reduce to acceptable levels of less than 0.001 torr. At these partial pressures, heat loss from the receivers is minimized and the plant will operate with maximum thermal efficiency.

Our latest work included transient modeling of a receiver annulus to predict the times required for hydrogen to permeate out of the receiver annulus. We modeled conditions in which the receiver tube is at the normal plant operating temperature and there is no hydrogen present in the HTF. The estimated times depended on the quantity of getter material in the receiver and the getter temperature and ranged from 2 to 10 months. We also modeled cases in which the receiver contained no getter material as a function of bellows temperature. The results were used to design laboratory experiments that determine the times required to purge hydrogen from the receiver annulus by permeation through the receiver tube wall and bellows.

4. Experimental Design

To substantiate the modeling results, we designed and constructed a laboratory experiment that determines the time required to purge hydrogen from a receiver annulus as a function of receiver tube and bellows temperatures. The tests use a receiver that contains no getter material and has a glass extension welded to the receiver glass. The extension provides access to the receiver annulus and allows the annulus to be evacuated and backfilled with hydrogen to a specific partial pressure. A schematic of the gas-handling equipment is shown in Figure 5.

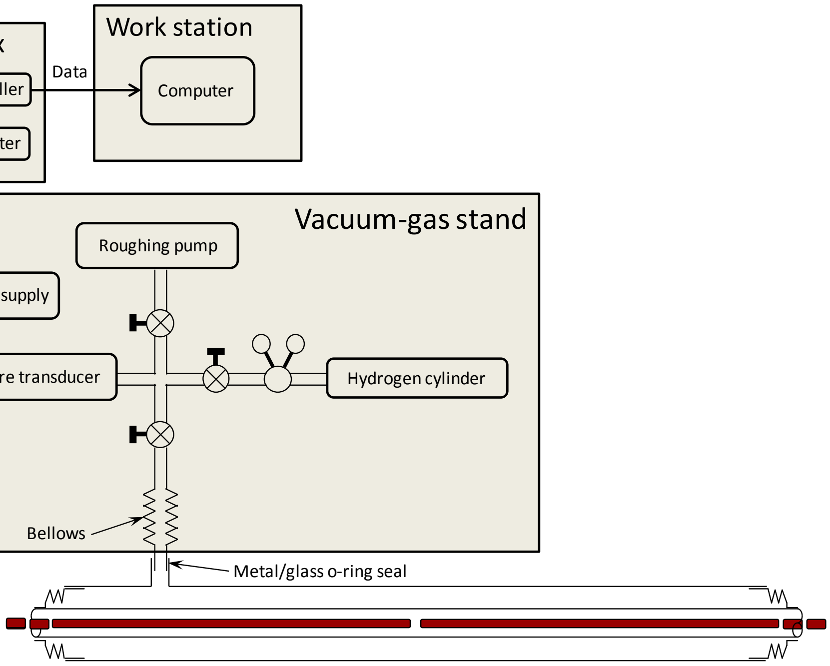

Figure 5. Gas-handling hardware and controls for experimental test setup.

The receiver is equipped with multiple electric heaters that are located within the receiver tube (Fig. 6). Two linear-cartridge heaters provide heating to the receiver tube and are able to maintain the tube at 400°C. Four coil heaters (two on each end) maintain the temperature of the receiver tube ends and prevent axial temperature gradients. Thermocouples provide temperature measurements of the heaters, receiver tube, glass tube, and bellows. Computer-based feedback control maintains the receiver tube at the desired temperature (400°C). The bellows are insulated in a manner that replicates the bellows insulation at the SEGS power plants in Kramer Junction, California.

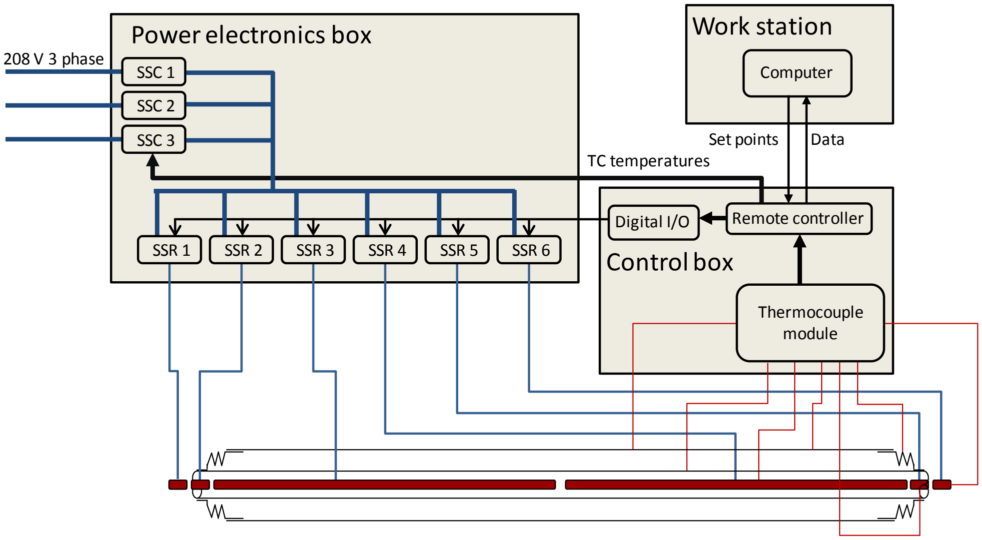

Figure 6. Heater hardware and controls for experimental test setup

Standard tests consist of evacuating the receiver annulus and backfilling with hydrogen to a pressure of 1 torr. The receiver annulus is sealed and isolated. The receiver tube is heated to 400°C for 8 hours each day to simulate operation at a commercial power plant. The temperature of the glass tube is monitored when the receiver tube is at 400°C. Initially, when hydrogen is present in the receiver annulus, the glass temperature will be elevated to about 150°C. As hydrogen permeates out of the annulus, the glass temperature will decrease to about 50°C. These tests will provide valuable information on the expected response of the receivers in an operating power plant when hydrogen is purged from the expansion tank.

5. Current Results

Figure 7 shows annulus pressure at various active purge rates in mol/s from a single vent located on the expansion vessel. These results indicate that actively purging hydrogen from a centralized location within the power plant will reduce the receiver hydrogen pressures within the annuli to acceptable levels.

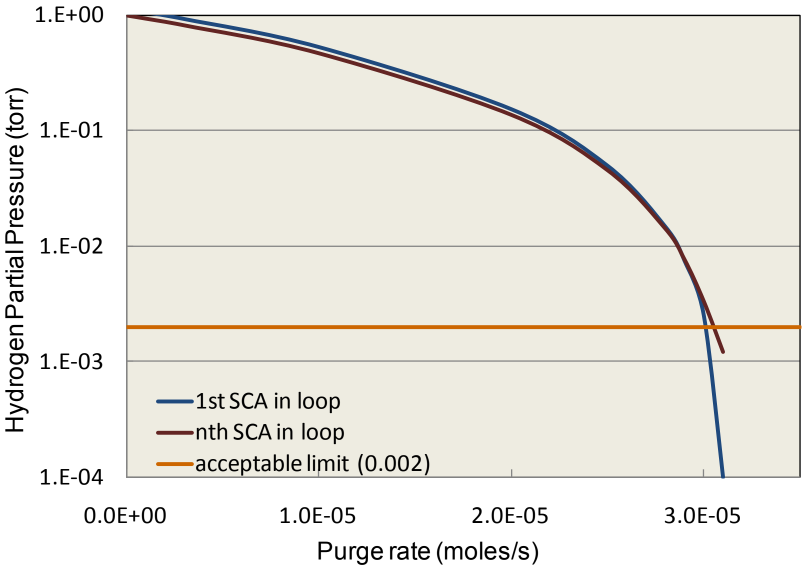

Figure 7. Steady-state annulus hydrogen partial pressure versus expansion tank purge rate.

Figure 8 shows the estimated purge time to reduce the partial pressure of hydrogen within the receiver annulus by two orders of magnitude. At bellows temperatures of less than 150°C, essentially all of the permeation is occurring through the receiver tube wall. Under this condition, the required purge time is 17 days (8 hours per day). As the bellows temperature increases from 150°C, a greater portion of the permeation is occurring through the bellows walls. At 400°C, the time required to purge hydrogen has decreased to about 1 day. These results show that if the bellows can be maintained at temperatures close to 400°C, then they will account for most of the permeation. The relatively high permeation rate through the bellows is due to the fact that the bellows wall is quite thin (0.254 mm) compared to that of the receiver tube (3 mm).

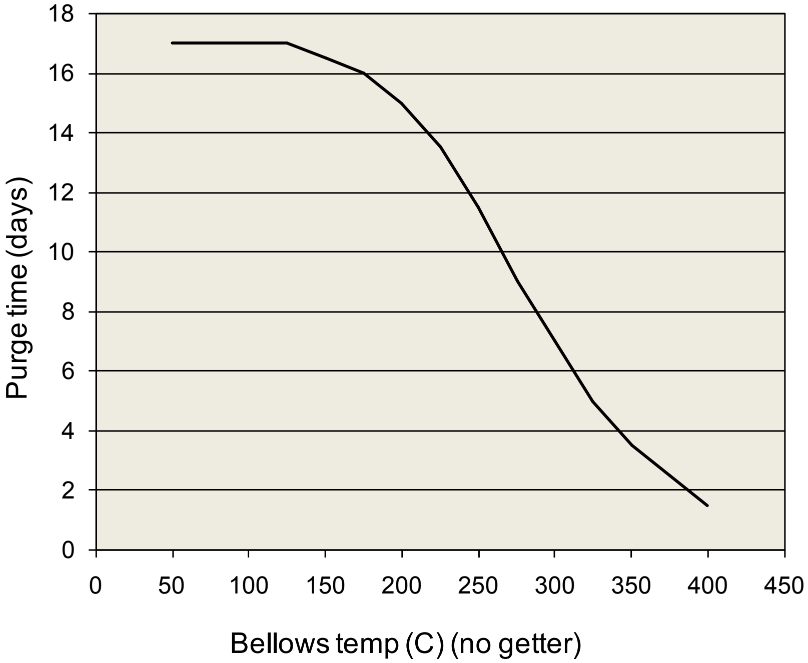

Figure 8. Hydrogen purge time versus receiver bellows temperature.

The experimental hardware shown in Figures 5 and 6 has been fabricated and assembled. The heaters, computer software, and safety controls are going through their final checks to ensure that they function properly when testing begins. In the next few months, we will conduct a series of tests to experimentally determine the hydrogen purge rates from the receiver annulus. Those results will be compared to the results that were predicted by the modeling work.

6. Future Work

Our intention is to demonstrate a method to remove hydrogen centrally from an operating, commercial parabolic trough power plant. We have identified a novel method to remove hydrogen from the HTF expansion tank of a parabolic trough plant. In March of 2010, a utility patent application for the method was submitted to the U. S. Patent & Trade Office. That application is currently patent pending. We have had discussions with several power plant owner/operators who have expressed interest in hosting a demonstration. Detailed discussions will not occur until the experimental testing described in this paper is concluded.

Acknowledgements

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14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS

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