On-Site Treatment of Brine

Final Report for the Work Performed at Penn State on the Design, Construction, and Preliminary Shakedown of a Mobile Brine Evaporator System during the Period 05/15/2001 to 05/14/2002

By

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ABSTRACT

Hart Resource Technologies, Inc. (HRT) and The Energy Institute at Penn State University have developed a unique process technology to provide a comprehensive wastewater treatment system to meet the wastewater disposal demands of the Appalachian oil and gas industry. The process will prove to be efficient and cost effective for the treatment of brine, which is a wastewater by-product of oil and gas production. Pending system optimization and field demonstration, this process will enable HRT to focus on those areas that have the greatest cost savings to the industry and positive effect on the environment.

HRT and Penn State have developed a mobile process to evaporate treated brine at natural gas well sites where the brine is generated. The system is designed such that all the equipment needed for the treatment and evaporation of the brine is contained on one mobile vehicle. Also, only one employee will be needed to perform the required pretreatment and evaporation process, which in turn will keep costs low.

The design and construction of the system have been completed. Approximately twenty hours of shakedown were performed at Penn State evaporating tap water with an additional 3-4 hours of shakedown using treated brine supplied by HRT. The system is currently being tested and optimized in the field by HRT. A number of areas for improvement and optimization have been identified from the initial shakedown period performed at Penn State.

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1.0 INTRODUCTION

Hart Resource Technologies, Inc. (HRT) and The Energy Institute at Penn State University have developed a unique process technology to provide a comprehensive wastewater treatment system to meet the wastewater disposal demands of the Appalachian oil and gas industry. The process will prove to be efficient and cost effective for the treatment of brine, which is a wastewater by-product of oil and gas production. This process will enable HRT to focus on those areas that have the greatest cost savings to the industry and positive effect on the environment.

Through researching previous failed attempts to provide on-site treatment of the brine, HRT discovered that pretreatment is necessary. HRT, who has perfected the pretreatment process at its existing plant in Creekside, Pennsylvania, teamed with The Energy Institute to develop a mobile process by which the metals could be removed and the remaining brine evaporated at the site where it is generated. A system has been designed for a natural gas well site where all the equipment needed for treatment of the brine is included on one mobile vehicle. Also, only one employee will be needed to perform the required pretreatment and evaporation processes, which in turn will keep costs low.

The brine, when brought to the surface, is separated from the natural gas inside a gas-liquid separator and stored in tanks adjacent to the wellhead. An example of a typical wellhead and brine tank located in western Pennsylvania is shown in Figure 1. Inside the brine tank there are three layers: the oil on top, the brine in the middle, and the sludge, which is a by-product from drilling natural gas wells, on the bottom of the tank. Quantities in each layer will vary. The first step in the treatment process will be to separate (on-site) the brine from the oil and tank sludge. Brine will be pumped into a second portable tank leaving a small amount in the brine tank to minimize other contaminants (oil or tank sludge) from being mixed into the liquid raw brine that is going to be processed. The brine will then be chemically treated for the purpose of dropping out the dissolved metals. This step in the process will be the same as that performed at the stationary HRT brine treatment plant.

Once the metals have been removed, the final step in the on-site processing will be the evaporation of the brine. The skid mounted system, designed and fabricated at Penn State, will be taken to the well site and operated for a sufficient period of time until all the treated brine has been evaporated leaving only a solid salt by-product. The project development of the on-site treatment system was broken down into three tasks:

- Task 1. Design of the Prototype Brine Evaporator;
- Task 2. Construction of the Prototype; and
- Task 3. Prototype Shakedown and Testing.

Figure 1. Photograph of a Natural Gas Well with a Gas-Liquid Separator and Brine Tank Located in Western Pennsylvania

Since it was agreed that the HRT pretreatment method could be applied on-site for the removal of the metals, the work on this project focused on the design and construction of the evaporation equipment. Tasks 1 and 2 have been completed and are reported in their entirety herein. In addition, shakedown testing that was conducted at Penn State using tap water and brine is reported herein. Work continues on Task 3, however, with HRT performing further testing and optimization at their facility followed by field tests. Those results will be reported separately by HRT in a follow-on report or as an addendum to this report. This testing is being reported separately since Penn State's involvement ended with the laboratory-scale shakedown testing.

In this report, the market for on-site treatment of the brine is discussed in Section 2.0, while the design, construction, and testing of the brine evaporator are presented in Section 3.0. A summary of the project is given in Section 4.0. Acknowledgements and references are provided in Sections 5.0 and 6.0, respectively.

2.0 MARKET FOR ON-SITE TREATMENT OF BRINE

The market for brine disposal encompasses all oil and gas producing regions in the Appalachian Basin, which includes New York, Pennsylvania, West Virginia, eastern Ohio, Kentucky, and Tennessee. Injection wells for the disposal of the brine have not been successful in most of the Appalachian Basin because of the low porosity and permeability within the rock, concerns with contamination of fresh groundwater flow, and the need for pretreatment of the brine prior to injection [1]. Therefore, this vast area must be covered by means of permanent centralized facilities for treating the brine.

HRT operates a brine treatment plant located in Creekside, Pennsylvania. The plant is located in Indiana County, as shown in Figure 2, at the edge of one of the largest natural gas producing regions in western Pennsylvania. Approximately 90% of the brine processed by HRT is generated from wells within 30 miles of the plant. The remaining 10% is transported from greater distances, as far away as West Virginia, Ohio, and New York. Although most of the brine originates within the surrounding counties of Armstrong, Jefferson, Clearfield, Cambria, Somerset, Westmoreland, Fayette, and Indiana, an average cost of $2.10 per barrel is spent on transporting the brine to the HRT plant. As shown in Figure 3, the transportation cost per barrel has continued to increase over the past fifteen years, while the disposal cost has decreased [2]. The cost for transporting brine is expected to continue increasing as the associated expenses (i.e., fuel, labor, and truck maintenance) continue to rise.

The development of this new portable brine treatment process will lower costs to producers with marginal wells, allowing them to be more competitive. The costs of on-site treatment will be considerably lower than centralized treatment due to the lower capital costs, fewer man-hours, and lower transportation costs. The only requirement for processing of the brine is an available supply of natural gas. Representatives from a number of companies, including Key Energy, Abarta, Kreibel Organization, and Phillips Production, have given assurances that the natural gas would be provided at no cost or at a reduced cost if their brine was processed at costs lower than what they are currently charged [3]. HRT estimates that through successful on-site treatment, brine could be processed for approximately $3 per barrel. This would represent a 40% cost savings for the producers. Also, less time is needed for on-site treatment making it possible that up to four different sites can be processed during a given shift of an employee, depending on the location, volume, and quality of the brine. HRT recognizes that this process technology

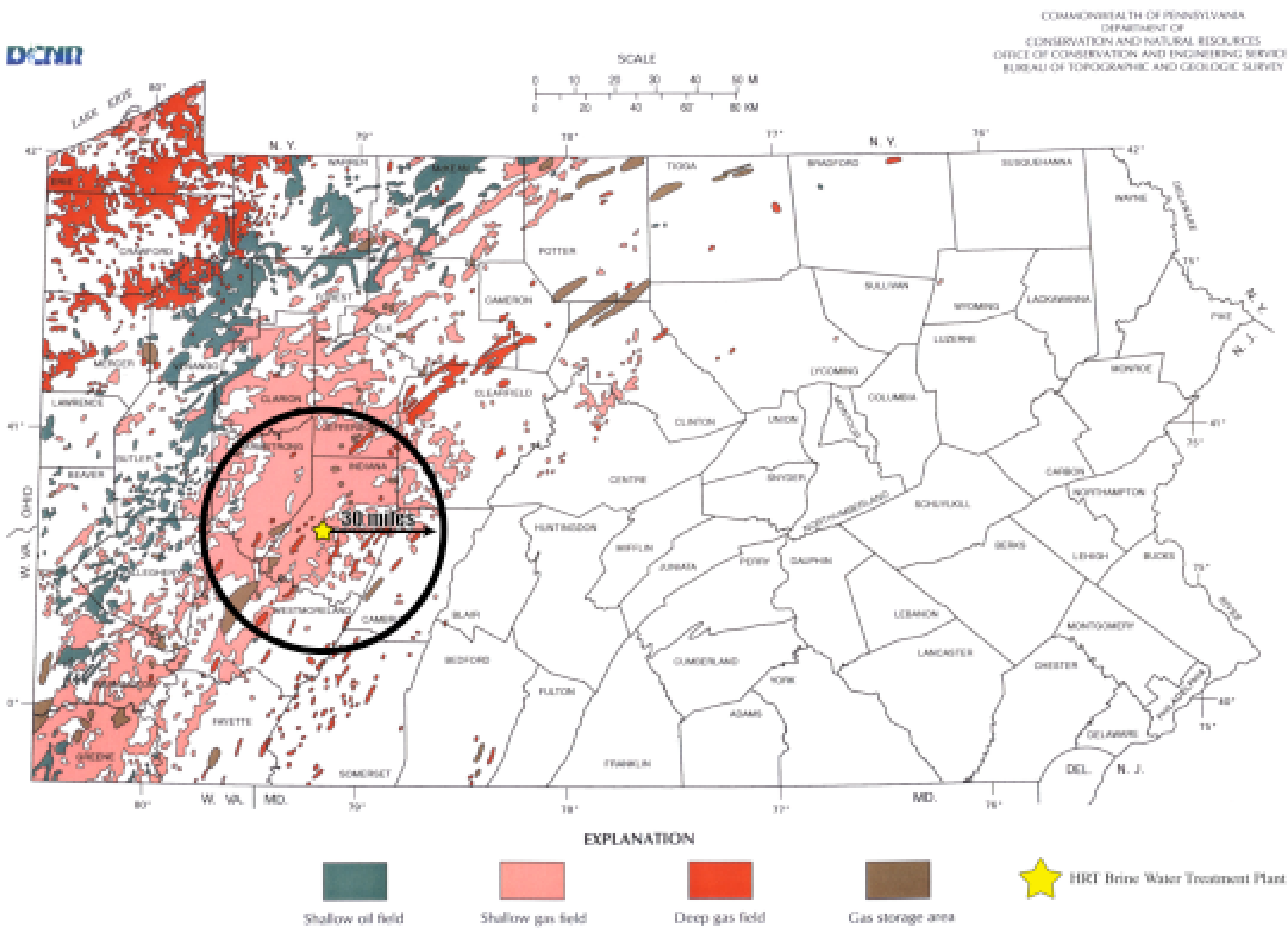

Figure 2. Location of the HRT Brine Treatment Plant with Respect to the Natural Gas Producing Regions in Pennsylvania

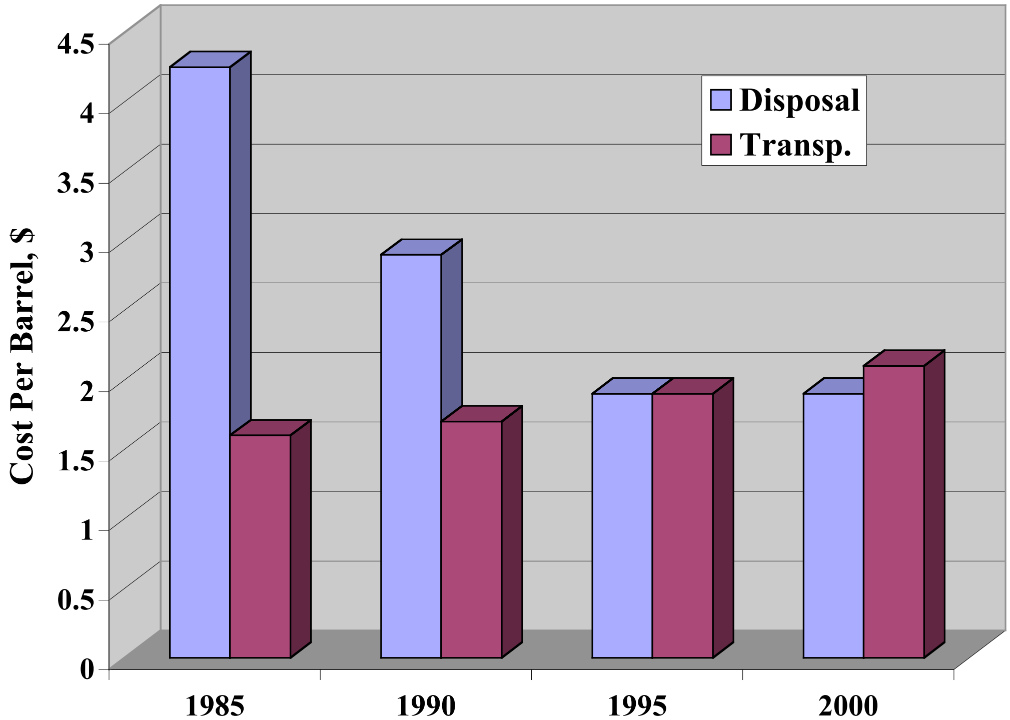

Figure 3. Disposal and Transportation Costs Per Barrel of Brine Treated

will drastically change the disposal market by providing the industry more convenience at a lower cost.

Salt is a salable by-product of the on-site evaporation of the brine. It has been estimated that an average of 1.5 to 1.75 pounds of salt (sodium chloride and calcium chloride) can be recovered from each gallon of brine evaporated. A market for the salt is currently being explored. However, salt produced through the operation of a 30,000 gallons per day evaporator/crystallizer at the HRT plant in the early 1990's was sold without any difficulties.

Table 1 is a typical analyses of the salt by-product provided by HRT and shows that over 95 wt.% is comprised of chlorides such as calcium chloride, sodium chloride, and magnesium chloride. Several minor constituents exist in much lower concentrations. The salt, although not of sufficient purity for food grade use, could be commercially available for dust suppression, roadbed stabilization, and for the control of ice on road surfaces. Hydgroscopic compounds, such as calcium chloride, have proven to be an effective agent to suppress dust and stabilize roadbeds. Commercial products in the form of solid salts have been effectively used for many years in road treatment.

Table 1. Typical Analysis of Salt Recovered Through Evaporation of Treated Brine

Major Constituents	**Weight Percent**
$CaCl_2$	20
NaCl	75
$MgCl_2$	2
$CaSO_4$	1
Minor Constituents	
$BaSO_4$	66 ppm
LiCl	240 ppm
Fe	2 ppm
Heavy Metals	< 5 ppm

3.0 RESULTS AND DISCUSSION

3.1 Preliminary Brine Evaporation Test

The original concept proposed to the Stripper Well Consortium was a two-step evaporation process [4]. Prior to purchasing the evaporator that was identified in the proposal for the first stage of the process (which was a major portion of the total equipment/ materials costs), a sample of treated brine obtained from the HRT plant was tested to determine the approximate salt content and the volume of brine that could be evaporated before a significant amount of salt crystals dropped out of suspension. This was necessary to ensure that the proper equipment/method for evaporating the brine was selected.

The test consisted of weighing and measuring the specific gravity of a 2-liter sample of the treated brine. The sample was then placed on a hot plate and the brine was boiled down until approximately 90% of the water volume had been evaporated. Periodically, the weight, specific gravity, and the formation of salt crystals were noted. The sample was then dried in an oven at 110°C (230°F) until all the remaining water had been evaporated. A final weight was recorded for the dried salt crystals.

A plot of the brine solution's specific gravity versus the percent of water volume evaporated is shown in Figure 4. A specific gravity of 1.13 was measured for the initial sample. As expected, the specific gravity increases as the water is driven off, reaching a maximum of 1.26 where approximately 55 vol.% of the water has been evaporated. It was noted that prior to this volume, a significant amount of salt crystals had formed in the solution. Although additional evaporation would be possible in the first step of a two-step process, there was concern that the required pumping of the resulting slurry to the second-stage evaporator might cause potential downstream plugging. Therefore, it was decided that a single-step method of evaporating the brine would be preferred. The resulting skid-mounted system was designed around this concept.

The total dissolved solids (TDS), including chlorides, in Pennsylvania brine water ranges from 2,000 to 200,000 parts per million (ppm) with an average value of 80,000 ppm. This is over twice the salinity of seawater, which is about 35,000 ppm (TDS). A salt content of 17.3 wt.% within the brine water was determined for this sample. This percentage was at the low end of the range of salt contents (17.0 – 29.9 wt.%) measured at Penn State for other treated and untreated samples [5]. Using this value, approximately 1.58 pounds of salt should be produced for every gallon of treated brine evaporated. This would represent a total of 4,740 pounds of salt recovered for the evaporation of a typical 3,000 gallon brine tank. Using a bulk density for the salt of 65 pounds/cubic foot, the volume of the recovered salt product was estimated at 73 cubic feet. This volume was used in designing the collection bin placed beneath the evaporation system.

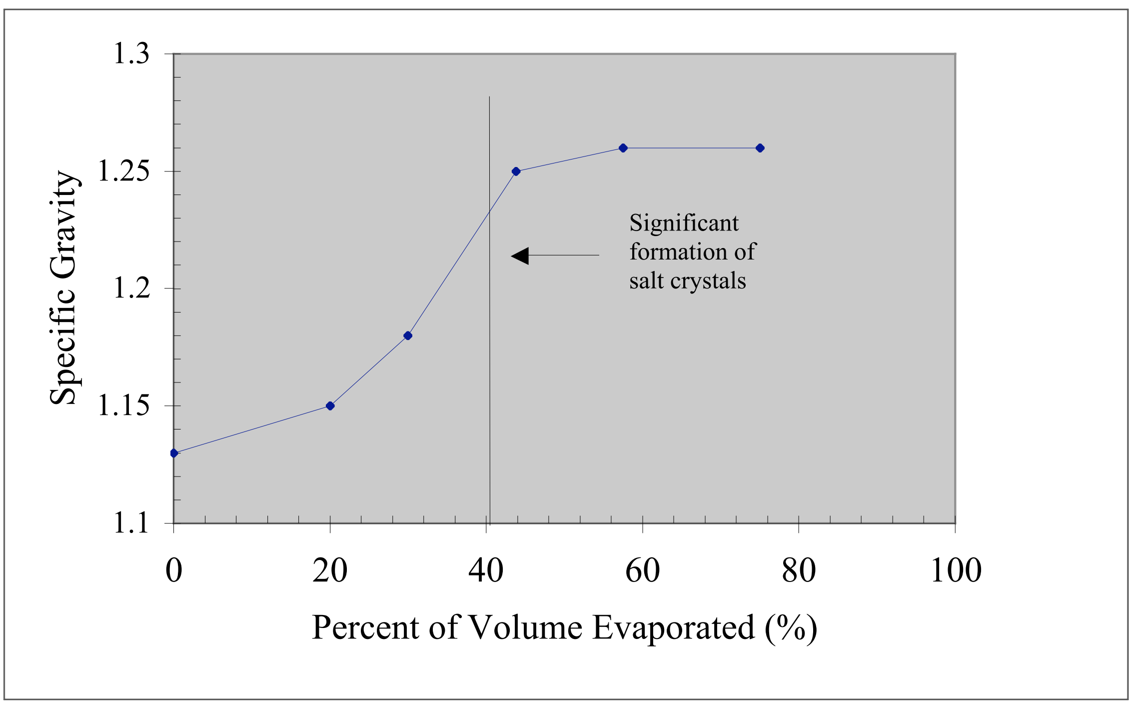

Figure 4. Specific Gravity of the Brine as a Function of the Volume Evaporated

3.2 Task 1 – Design of the Prototype Brine Water Evaporator/ Task 2 – Construction of the Prototype

The objectives of Tasks 1 and 2 were to design and construct the initial on-site brine evaporation prototype or process. Tasks 1 and 2 are being reported in one section because most of the design and construction work were conducted simultaneously with the exception of an initial design phase. It is difficult to completely separate the two phases as the design was ongoing as the construction proceeded.

Most of the effort focused on evaporating the pretreated brine, since it was agreed that the HRT pretreatment steps could be applied on-site for the removal of the metals. Therefore, the challenge was to design a skid-mounted system that could be transported to the well site on a small trailer (approximately 14 feet by 6.5 feet), connected to the brine tank and natural gas supply, and operated unattended until the available brine was evaporated.

The design process began with a review of earlier attempts of on-site treatment of brine. One such approach evaporated the brine within metal pans, burning wellhead natural gas to generate the energy for evaporation. One problem with this approach was that the crystallized salt settled to the bottom of the pan, insulating the remaining brine from the heat source. A second problem was that the units were prone to fires [6]. It also appeared that no pretreatment was performed to separate the harmful heavy metals from the brine. This step would allow beneficial use of the solid salt by-product with a reduced risk of these metals entering the surface or groundwater.

This review process also included discussions with a number of vendors who manufacture and supply evaporation equipment. Many types of evaporators were reviewed and two were selected for final consideration. These included a forced-circulation falling film evaporator and a rotary drum dryer. The first method utilized a two-step approach by which the brine would be concentrated within the falling film evaporator and then dried to a minimum moisture content inside a secondary device such as a spray-drying chamber. The second approach appeared well suited to dilute solutions and could accomplish the evaporation in a single step; however, its application to brine containing high dissolved solids was uncertain.

The solution to evaporating the treated brine would be strongly affected by the liquid's characteristics. Properties such as solids concentration, temperature sensitivity of the salts, liquid foaming, scaling, and corrosiveness (i.e., required materials of construction) must be considered. The falling film evaporator appeared favorable given the characteristics of the brine. Since the brine is high in salts, such as calcium chloride and sodium chloride, the water would start to form a scale during evaporation on the heat transfer surfaces. The brine would also become more corrosive as it was further concentrated. A falling film design with the heat transfer surfaces arranged in a vertical configuration, would allow high concentrations while maintaining high heat transfer rates, minimizing the build up of scale on the heat transfer surfaces.

Locating a supplier of a direct-fired falling film evaporator whose only energy source was the available supply of natural gas proved difficult. The use of steam in combination with mechanical vapor recompression is a common method of supplying the energy for evaporation is this type of evaporator. This approach, while being efficient, requires additional equipment and a supply of treated water to generate the required steam. Also, the required second-stage drying chamber must be sufficiently large to prevent the droplets from striking solid surfaces before drying takes place, resulting in large drying chambers. Diameters of 8 to 30 feet are common [7]. As a result, this type of evaporating equipment proved to be too costly and too large for providing portable on-site evaporation of the brine.

The second method of brine evaporation consists of a heated metal cylinder on the outside of which a thin layer of brine would be evaporated to dryness. The dried salt would be scraped off the cylinder as it slowly revolved. This approach offered the advantage that the rotary drum could be heated directly by a natural gas-fired burner. This single-step process also reduced the amount of equipment required for placement on the skid. Space was a great concern since a natural gas powered generator was required to supply the electricity necessary for the brine pump, motors, and system controls. Based on the results of this review and comments provided from experienced well site operators and owners, a single step skid-mounted system was conceived.

A generalized schematic diagram of the evaporation system is shown in Figure 5. The portable unit was designed to be transported to the wellhead where a brine tank, having an average capacity of 3,000 gallons, would be located. Brine would be removed from the brine tank, treated to remove the metals, and then pumped to the portable brine recovery unit, where the water will be evaporated, and the dry salt recovered. The desired processing flow rate of brine was 1 gallon/minute, in order to process a 3,000-gallon tank in approximately two days. The skid-mounted unit will be started up by a technician who will then leave the unit unmanned until it has successfully evaporated all the brine, at which time the technician will return to the site to recover the dry salt that was produced.

The evaporation system must be self-contained, requiring only a supply of natural gas to complete the evaporation of the brine. The supply of natural gas can be tapped

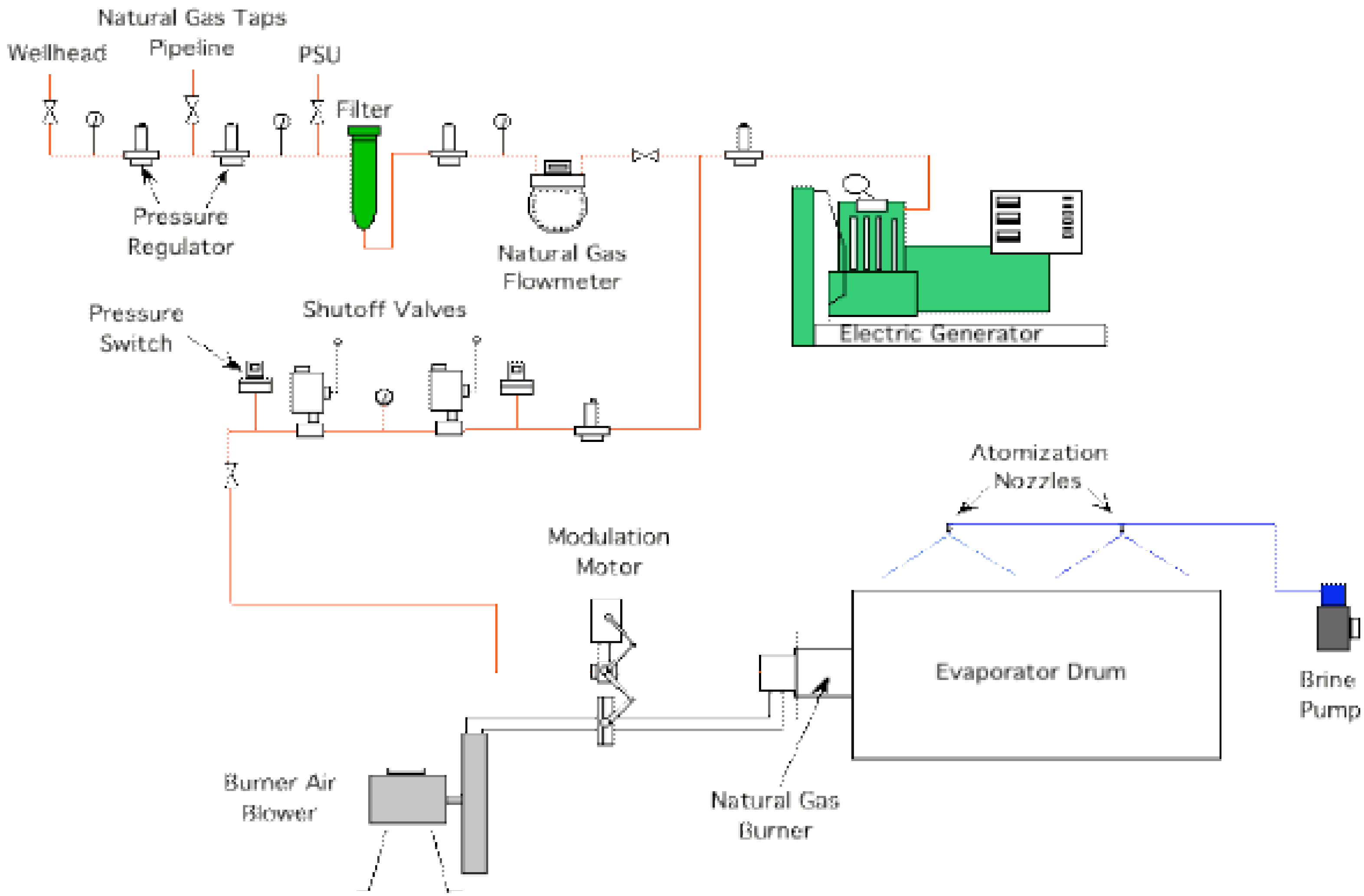

Figure 5. Generalized Schematic Diagram of the On-site Brine Evaporator

from either the wellhead or the main line. Depending on the source, the supply pressure can vary. Natural gas supplied from the wellhead can exceed 1,400 pounds per square inch (psig), while gas supplied from the main line will be approximately 400 to 500 psig. To accommodate these pressures and the low pressure (17 psig) available at the University for shakedown testing, three connections where installed on the entrance to the main gas train. These connections are shown with the in-line gas filter in Figure 6. A series of pressure regulators reduce the supply pressure down to 5 to 15 inches of water column prior to supplying the electric generator and gas burner. The filter was installed to remove any particulate matter and water from the natural gas. The maximum natural gas pressure that the system can handle is 1,480 psig.

A flowmeter was placed in-line to measure the rate of natural gas consumption during evaporation of the brine. This information will be useful during HRT's field testing to provide a means of evaluating the system's efficiency (i.e., cubic feet of natural gas consumed per gallon of brine water evaporated). Also indicated in the photograph are the drum and the gears which rotate the drum between 1 and 3 revolutions per minute.

After the flowmeter, the natural gas is supplied separately to the electric generator and the burner gas train. These portions of the system are shown in Figure 7. An Onan 7.5kVA natural gas generator set was selected and installed to provide the 220V AC service (maximum 30 amp supply) necessary to operate the brine pump, the burner blower, the drum rotation motor, and the burner controls. The maximum rate of natural gas consumed by the generator set at full load is approximately 95 cubic feet per hour. During normal operation of the brine evaporation system, well below full load demand will be placed on the generator set.

A 2 inch series "G" KINEMAX burner, gas train, and control package were purchased from the Maxon Corporation to provide the heat necessary for evaporating the brine. The maximum firing rate for the burner is 1.0 million Btu/hour. This style of burner was chosen because of its ability to operate at very high excess air levels, thereby allowing greater flexibility in the output gas temperature introduced into the rotary drum dryer.

The burner and gas train were designed to comply with the National Fire Protection Association Code. Although the pilot will automatically light when the generator set is running and the control panel is turned on, the operator must manually open the gas supply for the main flame when the system is first started. This step in the start-up procedure

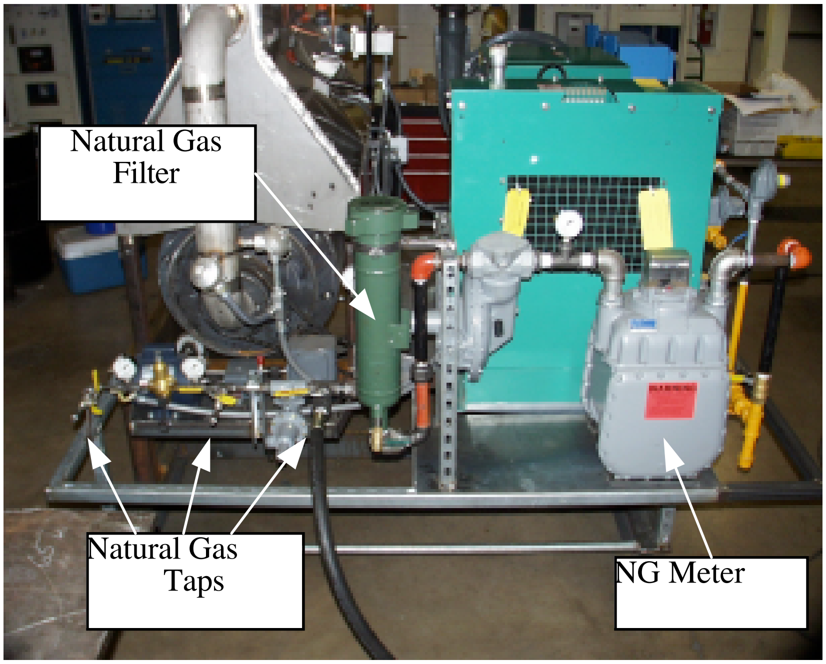

Figure 6. Photograph of the Prototype On-site Brine Treatment System Indicating the Natural Gas Taps, the In-line Filter, and the Flowmeter

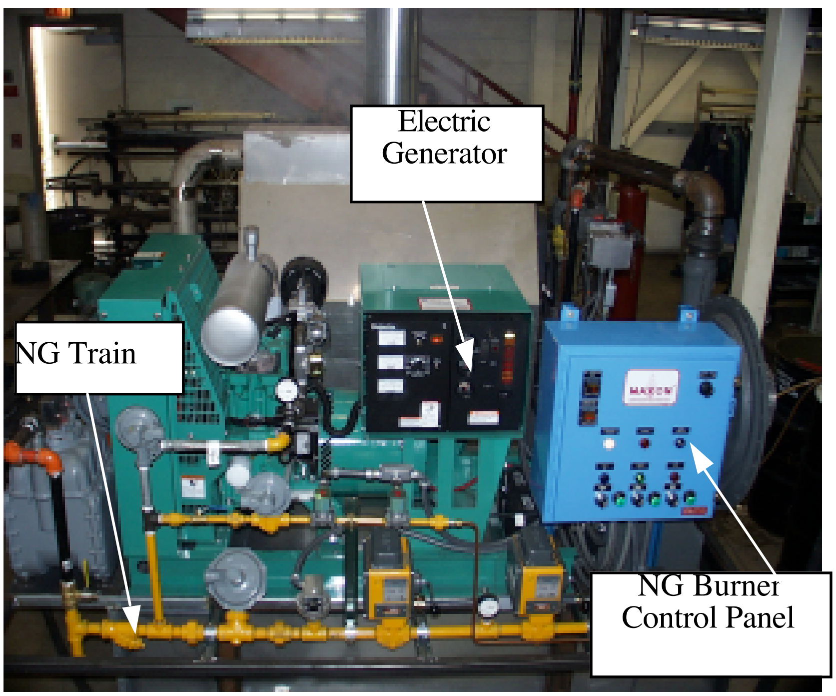

Figure 7. Photograph of the Prototype On-site Brine Treatment System Indicating the Electric Generator, N.G. Burner Control Panel, and Gas Train

allows the operator to verify that all safety conditions have been met before starting the evaporator. Additional safeguards that were installed include: 1) the combustion air blower must be operating before the main gas valves can be energized; and 2) the main gas valves must be energized and the drum rotating before the brine can be delivered to the evaporator. Several additional safeguards were identified during the initial shakedown and testing and are discussed in Section 3.3.

The combustion air blower, gas burner, and brine pump are shown in Figure 8. Natural gas and combustion air are both introduced to the burner through a Micro-Ratio valve. Connected by mechanical linkage to a series 72 Modutrol IV motor, the valve regulates the amount of natural gas burned to supply the heat required by the evaporator. A Barber Colman Model 7SC temperature controller allows the system to maintain a constant flue gas temperature at the exit of the evaporator drum. A type K thermocouple monitors this temperature while a second type K thermocouple along with a Barber Colman Model 7SL High/Low Limitrol provide overtemperature protection for the evaporator.

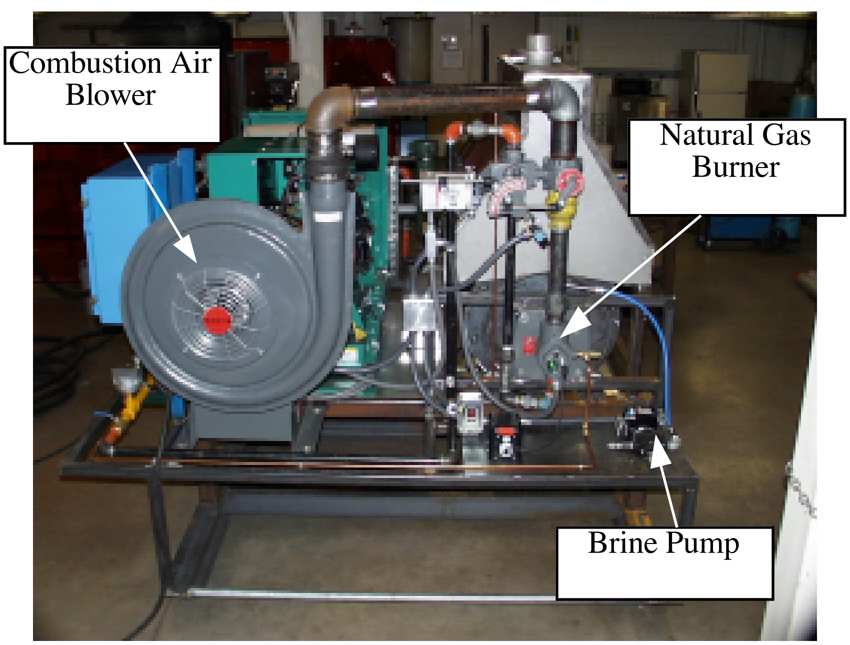

Figure 8. Photograph of the Prototype On-site Brine Treatment System Indicating the Combustion Air Blower, Gas Burner, and Brine Pump

A diaphram pump was selected to deliver the brine from the pretreatment tank to the evaporator. This pump, a model 31801 manufactured by Jabsco, has excellent resistance to corrosive attack by brine solutions. A second advantage of this type of pump is its ability to self prime when positioned up to 9 feet above the liquid supply level. This may be important when the evaporator skid must be located some distance on an upgrade from the pretreatment tank. The pump is capable of providing in excess of 2 gallons per minute of brine at 45 psig, more than sufficient pressure and flow rate for the atomization nozzles initially selected.

The corrosive and abrasive nature of the brine require that consideration be given to the materials of construction. Common materials used in contact with salt solutions include titanium, 317L stainless steel, CD-4MCu, Incoloy 825, and Alloy 20. CD-4MCu is a cast corrosion and heat resistant stainless steel alloy with good abrasion resistance. Incoloy is a high-grade nickel chromium iron alloy [8]. Since the final size and geometry of the inside baffling was uncertain, the evaporator drum was initially constructed out of carbon steel. This would allow modifications to be easily made to the evaporator drum at low cost. In a commercial application, the final drum will be constructed from a more appropriate alloy. All of the lines used to transport the brine are made of either chemically resistant tubing or 316 stainless steel. The containment hood above the evaporation drum is also fabricated with stainless steel.

The evaporator drum is 2 feet in diameter by 3 feet in length. A row of 2 to 4 nozzles are used to apply the pretreated brine onto the top surface of the drum as it revolves at 1 to 3 revolutions per minute. The evaporator drum and atomization nozzles are shown in Figure 9. Not shown in the figure is the knife blade used to remove the dried salt product. The blade was positioned to allow 3/4 rotation of the drum before removal of the dried salt product. This would result in a drying time of 0.25 to 0.75 minutes where the salt is in contact with the hot metal. With high heat-transfer coefficients from 220 to 360 Btu/ft^2-h-°F under optimum conditions, this should allow sufficient time for the brine to be dried to less than one percent moisture without damage to the salt product.

Once removed from the drum, the dried salt falls into a collection bin located on the skid beneath the evaporator. The bin was constructed of stainless steel with sufficient volume to hold approximately 2,400 pounds of salt. The bin was designed for easy clean out using fold-down end gates. To ensure that the entire bin volume was utilized, a spreader paddle was installed just beneath the evaporator and was geared to the same motor used for rotating the drum.

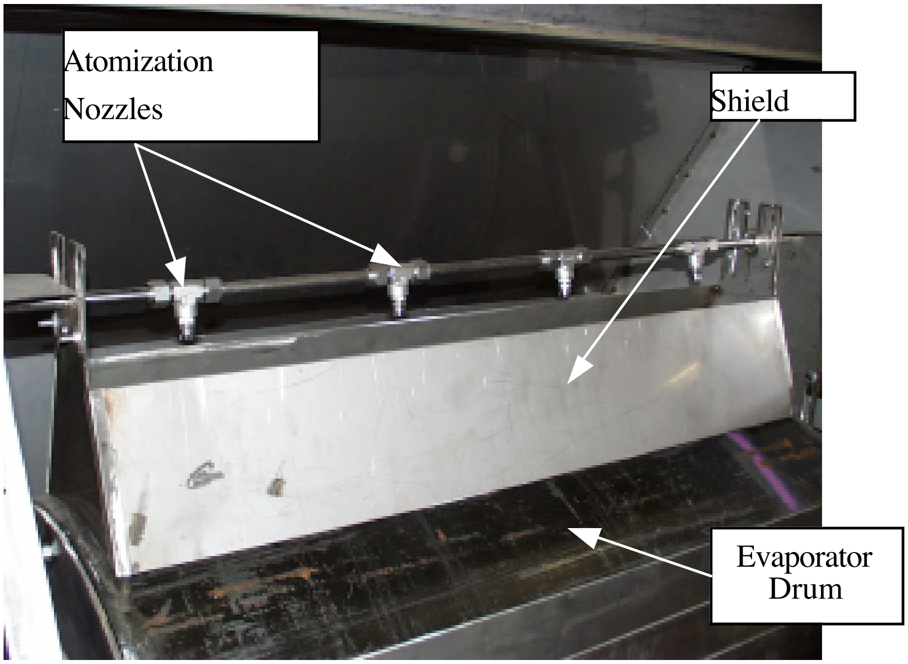

Figure 9. Photograph of the Prototype On-site Brine Treatment System Indicating the Evaporator Drum, Application Nozzles, and Shield

3.3 Task 3. Prototype Shakedown and Testing

Approximately 24 hours of shakedown were performed at Penn State after the prototype was constructed. The objective of the first portion of the testing was to evaluate the system's performance while evaporating tap water. This was followed by 3-4 hours of testing using treated brine obtained from the HRT plant. During the shakedown testing, no problems were encountered with the gas delivery system to either the natural gas generator set or the burner. However, a supply pressure of only 17 psig was available at Penn State, therefore, the use of higher supply pressures possible at the wellhead (1,400 psig) will be evaluated during testing in the field.

The generator set was sized such that under normal operating conditions well below full load demand is placed on it. However, during initial startup of the combustion air blower, the single phase, 2 horsepower motor draws approximately 60 amps, placing an excessive load on the generator set. This can be prevented through the use of an inverter and a three-phase motor to slowly increase the blower's speed, thereby considerably reducing the power draw on startup.

Once the mechanical linkage for the natural gas burner was properly adjusted, the burner was easily lit and the firing rate was controlled to deliver a constant drum exit temperature. The burner was primarily operated in the manual mode for much of the shakedown testing; however, several hours of operation in the automatic mode were also performed to test this part of the controls. The small amount of drift observed in the outlet temperature can be eliminated through tuning of the controller. An approximate metal surface temperature of 550 to 650°F was achieved without the application of brine and an outlet temperature of 850°F. This surface temperature dropped to approximately 450 to 550°F when either tap water or brine was applied at 0.1 gallon per minute per nozzle.

A limitation of this type of dryer is that the drying capacity is proportional to the active drum surface area. The recommended skid size limited the drum's active surface area to 14.1 square feet. A nozzle configuration using four BETE-type NF fan nozzles, each capable of delivery 0.25 gallon per minute, was first tested. However, the total flow rate of 1.0 gallon per minute proved too high to evaporate all of the water. Therefore, smaller nozzles were tested to determine the maximum flow rate the system could handle. Without increasing the skid size, a maximum of 0.24 gallon per minute of brine can be evaporated with an outlet temperature of 850°F. This is below the desired processing rate of 1.0 gallon per minute. Therefore, additional suggestions, including increasing the metal temperature and changing the method of applying brine to the drum need to be considered. Figure 10 is a photograph showing the evaporator processing brine during the early shakedown testing.

The rate of natural gas consumption during evaporation of either the tap water or brine was approximately 250 standard cubic feet per hour, or 250,000 Btu/hour. Slight changes to the internal drum baffling will decrease this rate and improve the evaporator's efficiency.

Consistent removal of the dried salt from the drum surface is important in maintaining good heat transfer to the fresh brine layer. The original design of the knife used for this purpose was rigid and did not allow for expansion of the drum during continued heating. Therefore, a redesign of the knife blade is required, allowing it to flex with changes in the drum's exterior.

Finally, the shakedown testing indicated that a number of control/safety sensors should be added to improve the evaporator's performance. These include a flow switch on the brine supply line and a bin level sensor, both of which would shut down the evaporator when either all the brine has been processed or the salt bin is full.

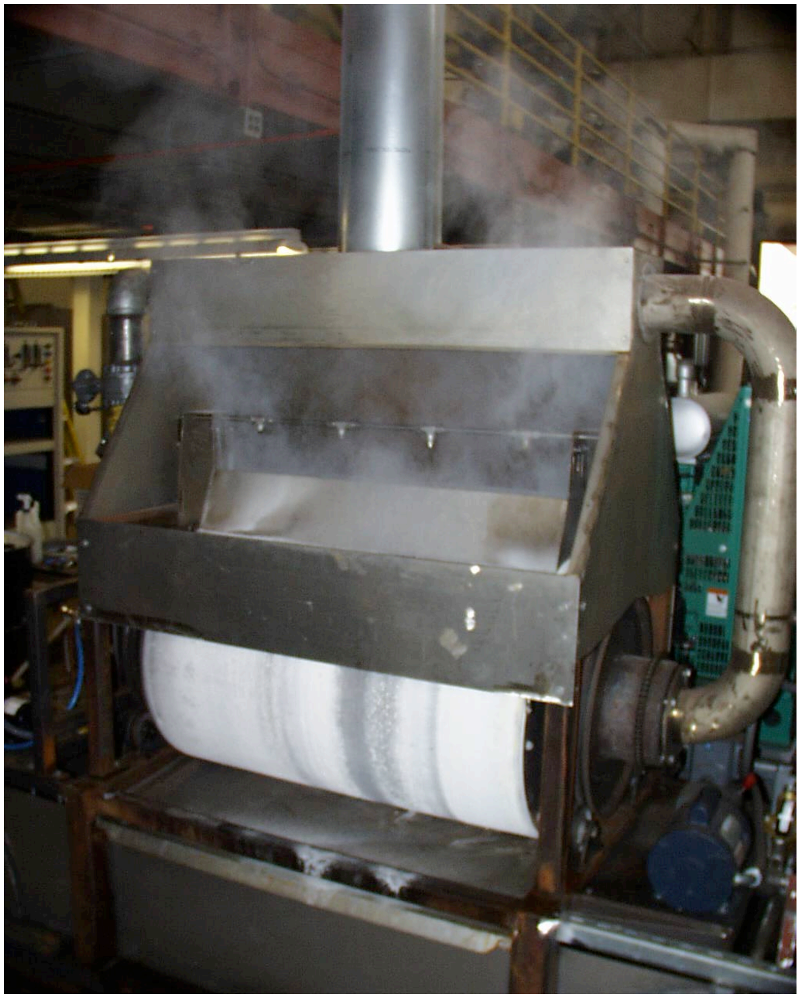

Figure 10. Photograph of the Brine Evaporator During Early Shakedown Testing

4.0 SUMMARY

HRT and Penn State's The Energy Institute have developed a unique process technology to provide a comprehensive wastewater treatment system to meet the wastewater disposal demands of the Appalachian oil and gas industry. The process will prove to be efficient and cost effective for the treatment of brine, which is a wastewater by-product of oil and gas production. Pending system optimization and field demonstration, this process will enable HRT to focus on those areas that have the greatest cost savings to the industry and positive effect on the environment.

HRT and Penn State have developed a mobile process to evaporate treated brine at the natural gas well site where the brine is generated. The system is designed such that all the equipment needed for the treatment and evaporation of the brine is contained on one mobile vehicle. Also, only one employee will be needed to perform the required pretreatment and evaporation process, which in turn will keep costs low.

The design and construction of the system have been completed. The system, which was originally conceived of consisting of a two-stage evaporation process comprised entirely of off-the-shelf components, went through extensive redesign resulting in a prototype containing components fabricated in-house as well as some purchased from vendors.

Approximately twenty hours of shakedown were performed at Penn State evaporating tap water with an additional 3-4 hours of shakedown using treated brine water supplied by HRT. A number of areas for improvement and optimization have been identified from the initial shakedown period performed at Penn State. Further testing was not performed at Penn State because of the unanticipated intensive labor effort for the system redesign and component fabrication. Consequently, the system is currently being optimized and tested by HRT, the results of which will be summarized in a separate report or provided as an addendum to this report.

5.0 ACKNOWLEDGMENTS

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