

Progress in Simulated Water Well Performance on Mars

Stephen J. Hoffman¹

The Aerospace Corporation, Houston, TX, 77058

James H. Lever²

*U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory,
Hanover, NH, 03755*

Alida D. Andrews³

The Aerospace Corporation, Houston, TX, 77058

Kevin D. Watts⁴

NASA Johnson Space Center, Houston, TX, 77058

Recent studies of human Mars missions considered the impacts of an abundant supply of in-situ, accessible water on these mission scenarios. Discovery of exposed water ice scarps in Martian mid-latitudes has bolstered the evidence for massive amounts of almost pure water in buried deposits in regions considered candidates for these future human missions.

This paper describes progress towards adapting a long-standing terrestrial technique for accessing and extracting water from these mid-latitude sources of ice. This approach relies on mechanical drills to access the ice through overlying debris. Once the ice layer has been reached, a technique known as a Rodriguez Well, or Rodwell, is used to melt the ice, store the resulting water in a subsurface cavity until needed, and then pump the water to the surface for use.

Previous work by the authors utilized a computer simulation to predict the performance of a Martian Rodwell. This simulation was originally developed to predict performance in terrestrial Polar Regions. Whereas the basic approach is appropriate for a similar well on Mars, several parameters had been empirically derived and required experiments simulating the Martian environment to determine the values appropriate for a Martian Rodwell simulation. These experiments have now been completed and preliminary values have been determined for the empirical parameters.

Test results are consistent with a dimensionless $Sh(Ra)$ correlation developed by Bower and Saylor (2009) and based on lab tests of water evaporating from a pool into a large air chamber. They are also consistent with correlations derived by Ingersoll (1970) and by Hecht (2002), based on natural-convection heat transfer. Each of these earlier correlations found $Sh \sim Ra^{1/3}$, with the 1/3rd power characteristic of large Ra where the boundary layer over the pool surface is turbulent. A somewhat surprising result was that this power-law was found to extend into a range of Ra where laminar flow would be expected. Another surprising result was found in that instead of following established correlations for natural-convection heat transfer over flat plates, the dimensionless heat-transfer rates (Nu) were much larger and approximately independent of Ra . This suggests that mass transfer from the pool enhances convective heat transfer, possibly by enhanced mixing in the boundary layer. Although this

¹ Engineering Specialist, Space Architecture Department, Human Exploration and Space Flight.

² Research Mechanical Engineer, Force Projection and Sustainment Branch.

³ Engineering Specialist, Space Architecture Department, Human Exploration and Space Flight.

⁴ Engineer, Exploration Mission Planning Office.

possibility has been suggested in the literature, if it is proven to be true under these conditions it could play an important role in the use of a Rodwell on Mars, where evaporative mass transfer is enhanced relative to terrestrial wells.

I. Introduction

Recent studies, carried out as part of NASA's ongoing examination of human Mars missions, considered the impacts of an abundant supply of in-situ, accessible water on these mission scenarios [1, 2, 3, 4, 5]. For these assessments, the elements of a human Mars mission that would most benefit from the largely unconstrained availability of water were identified and quantities of water likely to be used by crews in this "water rich" scenario were estimated. Sources of feedstock material from which water could be extracted were then identified based on the most recent available data for the surface of Mars. These feedstock materials tended to fall into two broad categories: regolith/minerals and ices. Assessments have been carried out for each of these feedstock types. Examples of assessments that use regolith/minerals as a feedstock can be found in the report by Abbud-Madrid, et al. [2] and the paper by Kleinhenz and Paz [3]. The papers by Hoffman, et al. [4, 5] provide a similar assessment of accessing and withdrawing water from subsurface ice deposits, using a combination of vertical drilling and a well-established terrestrial technique known as a Rodriguez Well or "Rodwell" [6]. Both approaches were found to be technically feasible. However, the scope and scale of the infrastructure needed to produce useful quantities of water in either approach was heavily dependent on assumptions regarding feedstock material characteristics and performance of the systems used to extract the water.

II. Computer Simulation

One recognized shortcoming of the Hoffman et al. assessment was the use of analysis tools – in particular, an engineering analysis tool designed to evaluate the performance of a Rodriguez Well under terrestrial environmental conditions [6] – that were not properly configured to simulate the Martian environment. Though the analysis tools and approach thus used by were appropriate for this preliminary assessment, several empirical parameters necessary to properly characterize the Martian environment simply did not exist. Values for these empirical parameters that were derived from experiments using similar Martian environmental conditions [7] were incorporated and results were reported [5].

The need to overcome this shortcoming and provide a more accurate assessment of accessing and using Martian water ice led to an experiment to determine the needed empirical parameters. This paper summarizes the design, development, and results of this experiment. A complete report of this experiment is in work.

The U.S. Army Corps of Engineers (USACE) Cold Regions Research and Engineering Laboratory (CRREL) developed its Rodwell computer simulation to design water wells for research stations on terrestrial ice caps, initially for South Pole Station, Antarctica (Lunardini and Rand [6]) and subsequently for Summit Station, Greenland (Haehnel and Knuth [8]). The time-domain simulation mimics the principal mass and energy exchanges through the cycle of water production and consumption for a Rodwell: a supply line from the station injects warm water into the ice, which melts ice to form a subsurface pool; a pump submerged in the pool pumps a portion of the melt water through a return line to the station; the station consumes some of this water for drinking, cooking and washing, etc.; waste heat from the station's generators reheats the remaining water to re-inject into the pool to melt new ice and thereby maintain the well. During operation, the pool grows larger and descends slowly into the ice cap, leaving a large air cavity above it. An ice cover generally forms on the pool surface, which decreases the pool-surface heat losses to the cavity. Eventually, pumping requirements from the deepening pool increase to the point that it is more efficient to start a new well nearby than to continue using the original one.

A simple lumped-mass energy budget forms the core of the simulation's calculations. Input parameters include ice density and far-field temperature, atmospheric temperature above the pool, injected water temperature and flow rate, water withdrawal rate, and station water-consumption rate. The energy budget solves for the water-production (ice-melt) rate by determining the net energy available at each time step after accounting for losses to the environment (see Fig. 1).

In Fig. 1, Q_{WI} from the water pool to the surrounding ice; Q_{WA} from the water surface into the air cavity; Q_{AI} from the cavity to the ice are shown. The CRREL simulation solves for the environmental heat flows and the corresponding pool and cavity temperatures, T_w and T_a , respectively, for specified mass and heat flows of injected warm water from the station and extracted water pumped to the station. The injected warm water causes the pool to melt ice as it slowly descends and widens.

The simulation allows the user to set well startup conditions to establish the water pool (initial borehole size, low input heat, no water withdrawal). Once the well reaches the target pool size, the simulation switches to user-established

water-injection, -withdrawal and -consumption parameters appropriate for summer (high) or winter (low) station populations. The available waste heat links injected water temperature and flow rate, which may be separately adjusted. Typically, the user seeks to ensure that a combination of water-injection, -withdrawal and -consumption rates provide a usable lifespan (typically 10 years). Through manual iteration, the user can seek to optimize the design to minimize power requirements or maximize life.

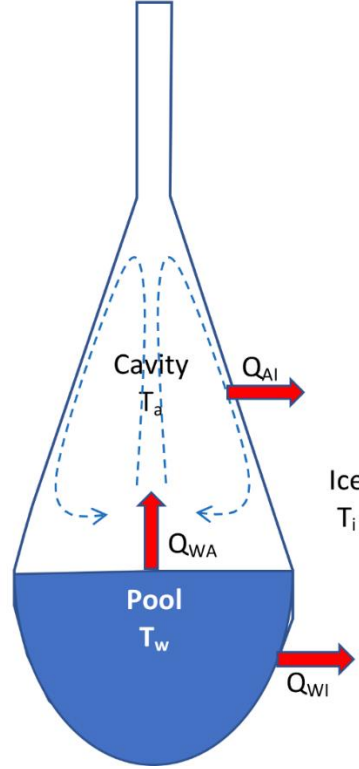


Fig. 1 Schematic of Rodwell showing heat flows to the environment

III. Empirical Parameters

Lunardini and Rand [6] used a range of $h_{wi} = 136 - 185 \text{ W/m}^2/\text{°C}$ based on published values for water flowing over ice at low velocities (laminar flow). This approach is considered reasonable for preliminary engineering calculations given that the water-ice interface should be similar for a Martian Rodwell. Numerical simulations can assess the sensitivity of predicted Rodwell performance on this parameter. Future detailed studies should investigate whether higher circulation velocities in smaller pools could substantially increase h_{wi} for Mars applications. These detailed studies could also assess the validity of lumping heat-conduction losses into an effective latent-heat value.

The water-to-air heat-transfer coefficient, h_{wa} ($\text{W/m}^2/\text{°C}$), determines the heat delivered to the cavity from the water-pool surface, Q_{WA} (W):

$$Q_{WA} = h_{wa} A_{wa} (T_w - T_a) \quad (1)$$

where A_{wa} is the pool surface area and T_a is bulk cavity (air) temperature. Natural convection, driven by warm, moist air rising from the pool and cooling as it descends along the cavity walls, governs this heat transfer. Lunardini and Rand [6] used $h_{wa} = 5.7 \text{ W/m}^2/\text{°C}$. Although they do not cite a source for this value, it falls within the range expected for turbulent, natural-convection heat transfer over a flat plate (Holman [9]).

The conditions on Mars that affect this flow are substantially different from those on Earth: lower gravity to propel the buoyancy-driven flow; CO_2 rather than air as the principal gas; pressure close to the triple point of water, 6.1 mbar. The low pressure, in particular, will enhance evaporation from the pool into the cavity, potentially increasing the heat-transfer rate significantly. After an ice cover forms on the pool, sublimation of the ice owing to low pressure could

increase heat transfer compared with comparable conditions on Earth. A series of small-scale tests were chosen to investigate these sources of potentially higher heat losses for this study.

The air-to-ice heat-transfer coefficient, h_{ai} ($\text{W}/\text{m}^2/^\circ\text{C}$), determines the heat removed from the cavity along the cavity walls, Q_{AI} (W):

$$Q_{AI} = h_{ai}A_{ai}(T_a - T_s) \quad (2)$$

where A_{ai} is the cavity surface area and T_s is temperature of the ice along the cavity walls. As with the pool temperature, Lunardini and Rand [6] modeled the cavity air and wall temperatures as bulk values (i.e., the values could change in time but had no spatial distribution). They modeled the heat conduction from the cavity walls into the surrounding ice based on an approximation by Lunardini [15], and they set $h_{ai} = 5.7 \text{ W}/\text{m}^2/^\circ\text{C}$, again without referencing it. As for h_{wa} , this value falls within the range expected for turbulent, natural-convection heat transfer over a flat plate (Holman [9]).

As noted, the natural-convection flow in the cavity could differ substantially on Mars. If evaporation from the pool is more significant than that experienced under terrestrial conditions, condensation and freezing of water vapor along the walls could increase heat transfer rates and hence heat losses to the surrounding ice. To assess this possibility, at least preliminarily, measurements of heat flux along the chamber walls were included as part of the small-scale tests described in this paper.

IV. Changes Needed for Mars Applications Parameters

Adjustment of many parameters in the CRREL Rodwell simulation from terrestrial values to those appropriate for Mars were cautiously made without violating physical principles upon which the simulation relies. Examples include the bulk or far-field ice temperature and density. The CRREL simulation uses measured density-depth and temperature-depth data from Antarctica or Greenland, including data that identify the depth at which water begins to pool rather than percolate through the firn (granular snow that has not yet been compressed into ice). For preliminary analyses, it was assumed that ancient water-ice deposits on Mars consist of fully compacted solid ice (density $917 \text{ kg}/\text{m}^3$) without an overburden of porous snow or firn. Bulk ice temperatures a few meters below the surface will equal the local average-annual surface temperatures at the sites of interest, say -60°C to -80°C on Mars (surface temperature measurements or model predictions are generally available for regions on Mars with ice deposits). This range is somewhat colder than Polar ice caps on Earth, but that difference alone does not change heat-transfer regimes. Thermal conductivity, diffusivity and latent heat of solid water-ice, which the simulation also uses, remain unchanged.

Many other model parameters are straightforward to adjust. For example, basic fluid properties (e.g., viscosity, conductivity, diffusivity, etc.) are available from handbooks. Similarly, far-field ice and air temperatures are simple input parameters.

However, the simulation's three heat-transfer coefficients that account for environmental heat losses warrant attention because the physical processes upon which they are based could be substantially different on Mars. We discuss each here briefly.

- First, the water-to-ice heat transfer processes (melting of, and heat conduction into, the ice walls) was judged to be similar on Earth and Mars, assuming that the massive ice deposits on Mars are essentially water ice.
- Second, the heat loss from the water surface to the cavity was judged to be the rate-limiting process governing cavity temperature.
- Finally, the associated heat loss from the cavity to the ice walls should be much faster, owing to condensation/freezing of the transported water vapor onto the walls. Nevertheless, we designed the small-scale tests to measure the cavity-to-wall heat transfer rates to compare with CRREL-model default values.

The water-to-ice heat-transfer coefficient, h_{wi} ($\text{W}/\text{m}^2/^\circ\text{C}$), establishes the heat delivered to the ice surface that bounds the water pool, Q_{WI} (W):

$$Q_{WI} = h_{wi}A_{wi}(T_w - T_m) \quad (3)$$

where A_{wi} is the surface area, T_w is the bulk pool water temperature and T_m is the melting temperature of ice, 0°C . Some of this heat conducts into the ice as an environmental heat loss and the remainder melts the ice to produce water. Lunardini and Rand [6] employed an approximation to account for the heat loss (via Lunardini [10]) that lumped it into an effective latent heat value.

For the water surface to the cavity heat transfer, Mars' atmosphere consists of almost entirely CO_2 at pressures close to the triple point of water (6.11 mbar, 0.01°C). There was thus a concern that evaporative heat losses from the

pool surface would be significantly greater than those for terrestrial water wells and could dominate heat losses until the pool skimmed over with ice. This study therefore sought to update the pool-to-cavity heat losses for a range of conditions slightly above the triple point, 8 – 10 mbar, assuming that the well would be created at a surface elevation where the ambient pressure would be at least this high or that it would be possible to pressurize the cavity slightly. To a lesser degree, this study also sought preliminarily to assess whether boiling would be difficult to control – the pool-surface temperature would need to remain below 2°C to avoid boiling at 8 mbar.

V. Theoretical Foundation – Scaling Analysis

Use of small-scale model tests under laboratory conditions to predict system behavior at full-scale or “prototype” conditions generally involves scaling analysis. The input variables that govern the key physical process are linked to the desired output variables through groups of dimensionless parameters. The appropriate dimensionless groups can derive from the governing equations, if these are well established, or from dimensional analysis if the equations are poorly known or complex. Provided the same physical processes govern both the model and prototype systems, the test-derived empirical relationships between the input and output dimensionless variables should hold true across all ranges of physical parameters, including fluid type, temperature and pressure ranges, gravity differences, etc.

The water-surface heat flux into the cavity consists of two main components: evaporation and convection. Evaporation heat flux derives from the mass flux of water vapor into the cavity owing to the vapor-concentration gradient and the latent heat needed to support that mass flux. Convection heat flux derives from the temperature gradient and flow over the pool surface. Natural convection within the enclosed cavity drives the flow field that governs both heat fluxes: warm, moist CO₂ rises from the pool surface and then cools and condenses/freezes water vapor onto the cavity ice walls as it descends.

Ingersoll [11] and Hecht [7] derived expressions for evaporation-driven heat flux from water surfaces on Mars based on analogies with published correlations of natural convection-driven heat flux from flat plates. The two expressions differ slightly, but both include the dimensionless Grashof number to characterize the strength of the buoyancy-driven flow field.

Bower and Saylor [12] conducted an experimental investigation into the evaporative mass flux generated by natural convection over a water surface and compared their results with the few previous experimental studies on the topic. They formulated their study to seek the correlation between dimensionless flow-field input parameters and dimensionless mass flux. This same correlation should, in principle, apply to Mars, and this study used it to guide experiment design. In the following sections of this paper, results from this study are compared with Bower and Saylor’s correlation and those of other published studies, including Ingersoll [11] and Hecht [7].

Figure 2 shows a schematic identifying the layout and variables relevant to the prototype and model water-well systems. In the scaling analysis presented, the SI units for each physical parameter are included.

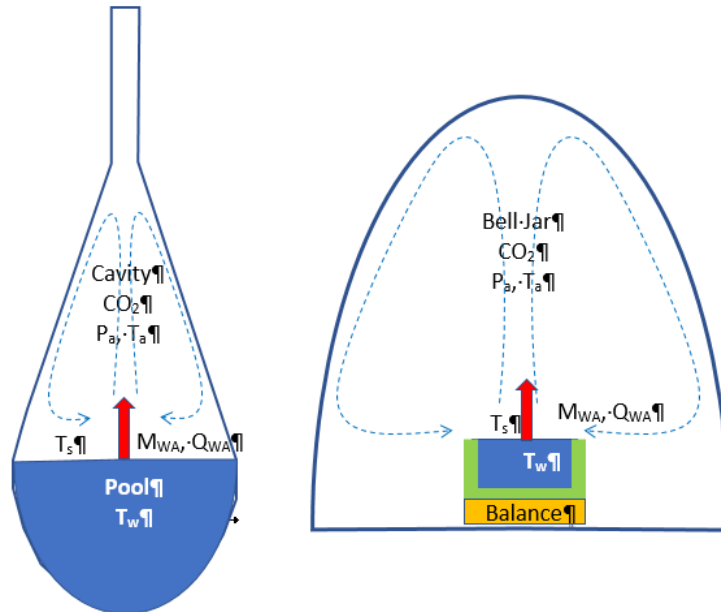


Fig. 2 Rodwell prototype (left) and small-scale model (right) showing key parameters and conceptual test layout (sketches not to scale)

In Fig. 2, M_{WA} and Q_{WA} are the mass and heat flows, respectively, from the water surface into the cavity or bell jar. T_w , T_s and T_a are the pool-bulk, water-surface and far-field atmospheric temperatures, respectively, and P_a is the atmospheric pressure. The dashed lines show the general direction of natural-convection atmospheric flow. Scaling analysis indicated that CO_2 was an acceptable working fluid for the tests.

Bower and Saylor [12] sought to determine the coefficients in a dimensionless relationship of the form

$$Sh = BSc^{1/3}Ra^n \quad (4)$$

where the empirical coefficients B and n are determined from laboratory measurements and are assumed to apply across similarly configured prototype systems.

The dimensionless mass-transfer coefficient (Sherwood number) is defined as

$$Sh \equiv \frac{h_m W}{D} \quad (5)$$

where W (m) is the pool diameter and D (m^2/s) is the diffusion coefficient (here, water vapor into CO_2).

The Schmidt number, Sc , relates the velocity and concentration fields

$$Sc \equiv \frac{\nu}{D} \quad (6)$$

where ν (m^2/s) is kinematic viscosity of the ambient fluid (here CO_2)

$$\nu = \frac{\mu}{\rho} \quad (7)$$

Absolute viscosity, μ , ($Pa \cdot s$ or kg/ms) of CO_2 depends only on temperature for moderate pressures, whereas CO_2 density varies with both temperature and pressure according to the ideal-gas law. Because temperature varies throughout the flow field, it is customary to evaluate temperature-dependent fluid properties at the “film temperature” or average temperature, $(T_s + T_a)/2$, between the water surface and the far-field atmosphere.

The Rayleigh number, Ra , establishes the buoyancy-driven flow field:

$$Ra \equiv \frac{g \Delta \rho W^3}{\bar{\rho} \nu \alpha} \quad (8)$$

where g (m/s^2) is gravitational acceleration and α (m^2/s) is thermal diffusivity

$$\alpha = \frac{k}{\rho c_p} \quad (9)$$

and k (W/mK) and c_p (J/kgK) are the thermal conductivity and specific heat of the fluid (CO_2).

The Rayleigh number can also be written as $Ra = GrPr$, where the Grashof number contains the buoyancy terms

$$Gr \equiv \frac{g \Delta \rho W^3}{\bar{\rho} \nu^2} \quad (10)$$

and the Prandtl number captures the relationship between the momentum and energy boundary layers

$$Pr \equiv \frac{\nu}{\alpha} \quad (11)$$

VI. Test-Parameter Selection

This study used the foregoing scaling analysis to guide the experiment design. Input parameter ranges were selected that would characterize Rodwells on Mars, Sherwood numbers were calculated for the expected input Rayleigh numbers, physical properties were selected for the model tests to overlap with those Rayleigh numbers, and then forecast the range of mass and heat-transfer rates expected in the model to select instrumentation to make the necessary measurements. The measured dimensionless mass-loss and heat-transfer rates were then compared with

those of the Bower and Saylor correlation to assess whether it applies across the broader Ra range on Mars and to assess any distortion in results caused by the configuration differences between model and prototype.

Bower and Saylor [12] found that $B = 0.230$ and $n = 0.321$ for $9.6 \times 10^5 < Ra < 5.7 \times 10^8$ for lab tests on water evaporating into air, with the water pool unconfined by the walls of the test chamber. Under these conditions, the Sherwood Number becomes

$$Sh = 0.230Sc^{1/3}Ra^{0.321} \quad (12)$$

Note that a potentially important model-to-prototype configuration difference pertains to the confining effect on the flow field by the cavity walls above the pool. The Bower and Saylor test configuration, and ours, minimized wall confinement, whereas the cavity walls above a Rodwell pool abut the water surface and geometrically confine the flow. Bower and Saylor noted that wall confinement can reduce the strength of dependence of Sh on Ra (i.e., reduce n). This study chose to delay investigating the role of wall confinement to follow-on tests that would more closely mimic a Rodwell configuration.

For this study the range of parameters for Rodwells on Mars were set as -60°C to -80°C , 8 – 10 mbar, pool diameter 0.1 – 4.9 m, with the small diameter corresponding to well startup. This provided a range $4.7 \times 10^3 < Ra < 5.7 \times 10^8$, again with the low end corresponding to startup. Note that the range of Ra for Mars Rodwells overlaps the range of validity of Equation (12) for pool diameters larger than 0.5 m.

Table 1 summarizes the target values for the 12 model-test points. The available bell jar was approximately 60 cm diameter and the internal cooling shroud could reliably achieve -40°C (test equipment details are described in the following section). Working within these constraints, this experiment was able to overlap most of the Ra range of interest using CO_2 as the atmosphere, a pressure range 8 – 1000 mbar, and pool sizes of 0.08 m and 0.14 m (based on commercially available dewars of 3 and 6 inches, respectively). The actual operating conditions of the tests varied slightly from these target values but still overlapped the Ra range of interest.

Table 1 Target operating conditions and Rayleigh numbers for the model tests.

Test Number	Dewar Size (inches)	Air Temp (deg C)	Air Pressure (mbar)	Rayleigh Number
1	3	-40	8	4.6E+03
2	3	-40	240	1.0E+06
3	3	-40	1000	1.7E+07
4	3	-20	8	2.5E+03
5	3	-20	370	1.0E+06
6	3	-20	1000	7.0E+06
7	6	-40	8	2.5E+04
8	6	-40	95	9.9E+05
9	6	-40	1000	9.1E+07
10	6	-20	8	1.3E+04
11	6	-20	250	2.6E+06
12	6	-20	1000	3.8E+07

The green and red values of Ra fell within and outside, respectively, of the valid range for Equation 12.

Figure 3 shows predicted Sherwood number versus Rayleigh number, $Sh(Ra)$, based on Equation (12), for Mars- and model-Rodwell conditions. It also shows Bower and Saylor's correlation. Note that the slight offsets of the test points and curves result from the small influence of Schmidt number, Sc , in Equation (12) for the atmospheric gasses

(CO₂ for Mars and model, air for Bower and Saylor) at the respective temperatures and pressures. The low-pressure test conditions provided a check on whether Equation (12) may be validly extended for $Ra < 10^6$.

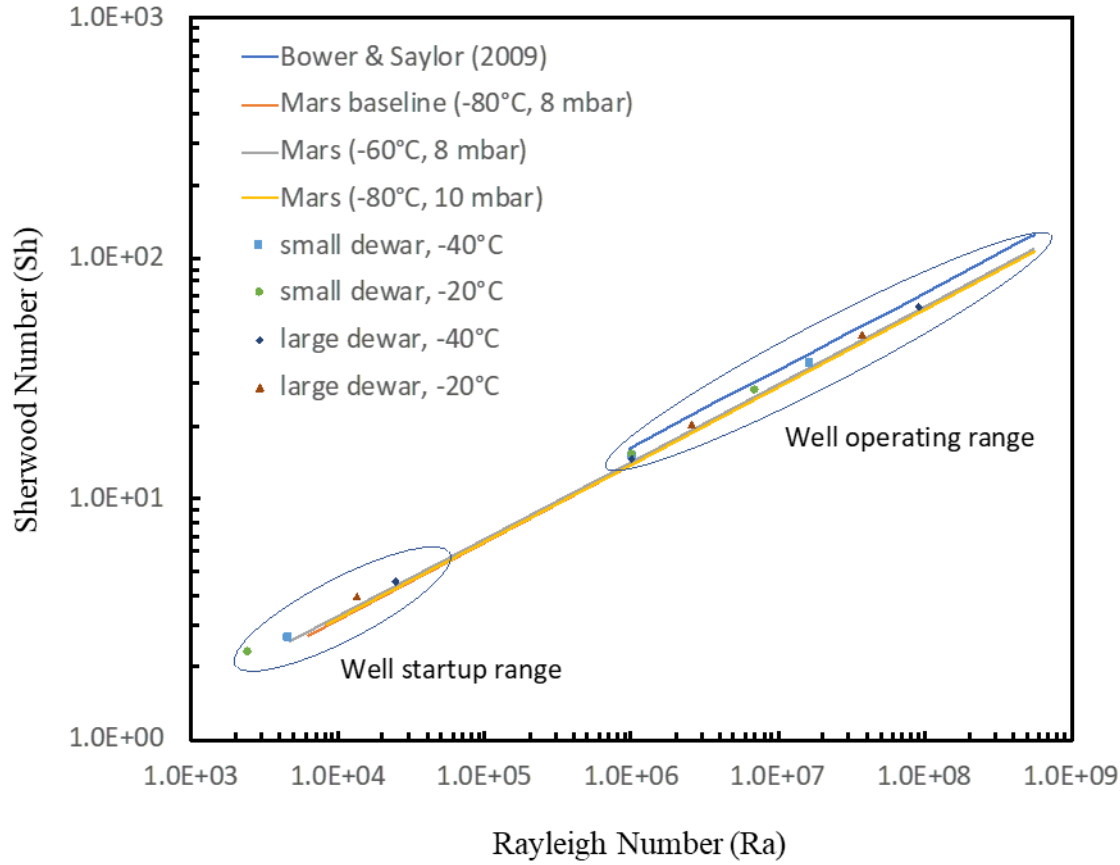


Fig. 3 Dimensionless mass-transport, Sh , versus dimensionless flow parameters, Ra , for evaporative mass loss from a water pool driven by natural convection above the pool

$Sh(Ra)$ values for Mars and our small-scale tests use the Bower and Saylor correlation (Equation 12), with the slight separation resulting from different values of Sc .

VII. Test Equipment

This study conducted 12 model tests during September and October 2019, with the sequence and target conditions listed in Table 1. These tests were conducted in a small instrumented bell jar located at NASA's Johnson Space Center (see Fig. 4).

The usable test volume in this bell jar measured approximately 2 feet in diameter and 2 feet tall (approximately 60 cm diameter by 60 cm tall). Pressure in this chamber could be reduced to near vacuum (lower than necessary for this test) and a thermal shroud inside the test area could establish temperatures near liquid nitrogen levels (also lower than necessary for this test).

Figure 5 shows the equipment used in this experiment and its general arrangement in the bell jar. The simulated Rodwell water pool was contained in a commercially available, hemispherical cryogenic dewar. This type of dewar was selected to minimize heat loss through the container itself and thus limiting the measurable heat loss to that of the water pool surface. The recirculating hot water typical of Rodwell operations was simulated with a submersible electric heater and a magnetic stirring bar.

This allowed the heat loss from the water pool to be measured by equating it to the amount of power needed by the heater to maintain a constant water pool temperature. Evaporative mass loss from the water pool was measured by a load cell mounted under the dewar.



Fig. 4 Bell jar test facility at the NASA Johnson Space Center.

Redundant resistance temperature sensors (RTDs) were mounted in the water pool to provide the feedback necessary to control power to the immersion heater. Three RTDs were mounted in the gas volume of the bell jar: one just above the surface of the water, one at the top of the cooling shroud, and the third midway between these other two RTDs. Heat flux sensors were attached to the cooling shroud wall at the same height as the three RTDs in the gas volume. A relative humidity sensor and pressure sensor were mounted with the mid-point RTD sensor.

A small stirring fan was mounted in the gas volume. This fan was used during the gas cool-down phase to enhance mixing and thus shorten the time to cool down to the temperature test point. Once the desired gas temperature had been achieved, this fan was turned off and any circulation in the gas volume was achieved by natural convection.

A small camera was placed near the top of the test chamber so that the evolution of the test could be observed. A single LED light was placed near this camera for illumination. An LED light was used to limit the heat input from this source.

A feed-through for water was used because of the method used to fill the bell jar with CO₂ gas for the test. When initially sealed, the bell jar is filled with 14.7 psi air at room temperature. The chamber is drawn down to vacuum and backfilled with CO₂ to 1000 mbar. The chamber is drawn down to vacuum a second time and backfilled with CO₂ to 1000 mbar. This was considered sufficient to remove non-CO₂ gas from the chamber. The small dewar was then filled with deionized water to the desired level from an external source and then the remainder of the test proceeded, beginning with the gas cool down. All of these sensors, the camera, the stirring fan, water feed-through, and the immersion heater were mounted to an external structure so that their mass and anticipated ice buildup would not be measured by the load cell.

One of the unexpected benefits of the camera was to document that an ice shelf formed just above the water pool when operating at all of the test conditions. The CRREL engineers regularly see an ice shelf of this type in large Rodwells, but they were not expecting to see this phenomenon at the small scale of this test. Consequently, a reduction in the exposed water pool area was taken into account when determining the results of this test (a 30% diameter reduction to account for the ice grown around the dewar rim at the pool surface). The camera also showed that water evaporating from the pool quickly froze on structures suspended above the pool and very little if any froze on the cooling shroud. This observation is problematic for those water extraction processes that assume ice can be melted below the surface, the water vapor extracted from the cavity, and condensation methods used to capture water above the surface. These observations indicate that the water vapor will quickly freeze to the subsurface cavity wall or any suspended equipment hanging in the well cavity.

Finally, the average cooling-shroud wall temperature (the average of the three heat flux sensor outputs) was used for the far-field atmospheric temperature, T_a , because the temperature difference between the wall and the pool drove the natural-convection flow.

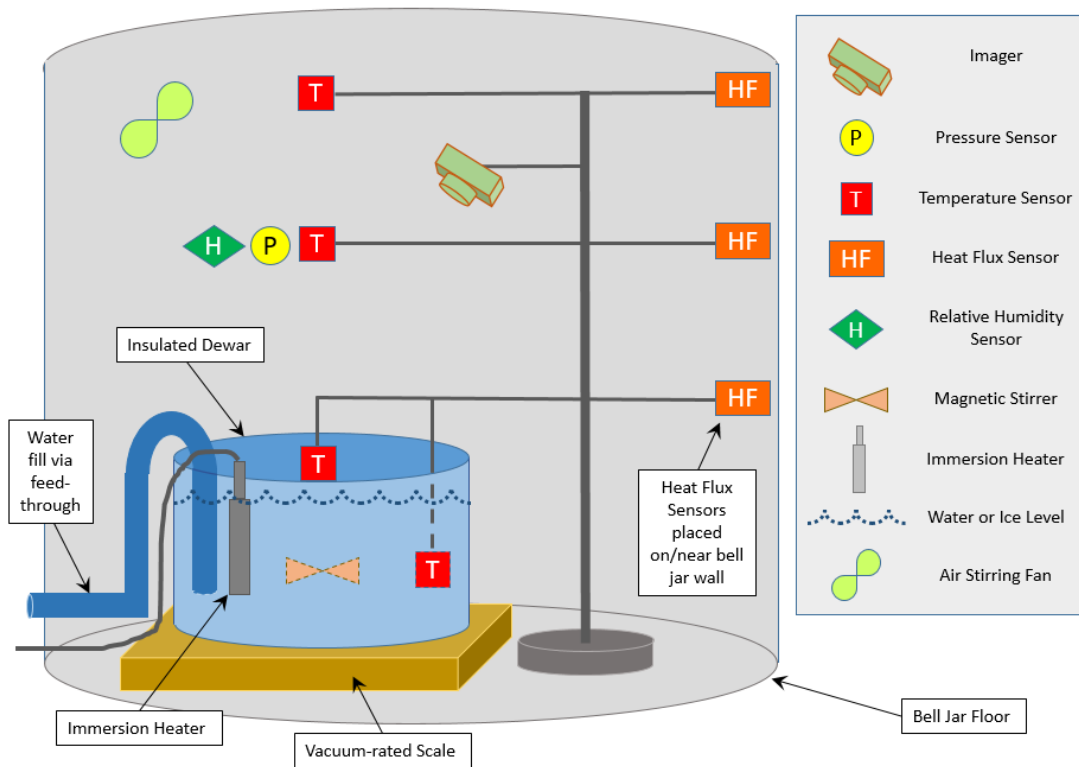


Fig. 5 Test equipment used inside the bell jar to gather heat transfer data relevant to Rodwell operations.

The planned test procedure was to cool the bell jar to the target temperature, pump down the CO₂ atmosphere to the target pressure, establish that conditions were steady, and then acquire the desired steady-state evaporative mass loss, heater power, and wall heat fluxes. Shakedown tests allowed several minor problems to be corrected:

- CO₂ pump-down was paused when bubbles formed in the pool to allow time for dissolved gasses to out-gas;
- The heater controller was adjusted to apply power smoothly and thereby avoid the local boiling on the surface of the cartridge heater;
- The wait times at each test point was lengthened to achieve steady state conditions more reliably; and
- Load-cell temperature was tracked to ensure that its readings were not drifting owing to changing temperature. Shakedown tests also allowed load-cell zero offset and scale factor to be calibrated as functions of temperature.

Unfortunately, a significant problem with drift in the steady-state load-cell data, later traced to a power supply, was unable to be corrected during the facility days allocated for the six small-dewar tests. Subsequent quality checks revealed that the mass-loss measurements were physically unrealistic for three tests (mass gain measured or evaporative power greater than heater power). Furthermore, the chamber pressure stabilized below the triple point pressure (6.1 mbar) for two other tests; boiling resulted, so the data were unusable to determine evaporative mass losses. Only one small-dewar test (Test 5) passed quality review, and its results may be unreliable because the load-cell signal drift was not fixed until after the small-dewar tests. Test 5 data were retained but the $Sh(Ra)$ correlation were assessed with and without including it.

During the scheduled downtime to swap dewars, the drift in the load-cell data was traced to a poorly functioning power supply and it was swapped out. The procedure for pump-down of the chamber was fine-tuned for the low-pressure test points. Subsequently, all six large-dewar tests (Test 7 – 12) passed quality checks. The stirring rate and temperature set point of the pool water were also slightly increased to limit the observed ice formation on the inner rim of the dewar.

VIII. Test Results

Details of experimental results and the heat transfer correlations that were derived from them, are described in the following subsections.

Evaporative Mass Transport. Figure 6 shows the dimensionless evaporative mass transfer, Sh , versus Ra for all seven good-quality tests (Tests 5, 7 – 12). Test 5 has minimal influence on the correlation $Sh(Ra)$ because it plots close to the best-fit line for the large-dewar tests (Tests 7 – 12). Also shown are several relevant published correlations, plotted across their valid ranges of Ra . Table 2 summarizes the coefficients in these power-law correlations of the form

$$Sh = C Ra^n \quad (13)$$

Note that each published correlation has been reworked to conform to Equation (13) to compare these predictions. The Bower and Saylor [12] correlation is Equation (12) with the average test value of Sc , which varied little, used to collapse it to $Sh(Ra)$. Similarly, the correlations of Sharpley and Boelter [13] and Boelter [14], as modified by Bower and Saylor [12], were collapsed for consistent parameter definitions.

Ingersoll [11] and Hecht [7] formulated evaporative mass-loss expressions based on analogies with published expressions for natural-convection heat transfer over flat plates:

$$\text{Ingersoll [11]} \quad Sh = 0.17 (Gr^*)^{1/3} \quad (14)$$

$$\text{Hecht [7]} \quad Sh = 0.15 (Gr^* Sc)^{1/3} \quad (15)$$

where Gr^* differs from Grashof number defined by Equation (10) through the use of the surface vapor- CO_2 mixture density, ρ_s , rather than the average mixture density, $\bar{\rho}$, in the denomination. That is,

$$Gr^* \equiv \frac{\bar{\rho}}{\rho_s} Gr \quad (16)$$

Cast in the form of $Sh(Ra)$, these expressions become:

$$\text{Ingersoll [11]} \quad Sh = 0.17 \left(\frac{\bar{\rho}}{\rho_s} \right)^{1/3} Pr^{-1/3} Ra^{1/3} \quad (17)$$

$$\text{Hecht [7]} \quad Sh = 0.15 \left(\frac{\bar{\rho}}{\rho_s} \right)^{1/3} Le^{1/3} Ra^{1/3} \quad (18)$$

where Lewis number relates thermal and molecular diffusion:

$$Le \equiv \frac{\alpha}{D} = Sc/Pr \quad (19)$$

As seen in Fig. 6, correlations from Bower and Saylor [12], Ingersoll [11] and Hecht [7], which all have $Sh \sim Ra^{1/3}$, all provide reasonable agreement with test data when extended well below their stated ranges of Ra validity. Note that the correlations of Ingersoll and Hecht derive from natural-convection heat-transfer valid in turbulent flow at much higher Ra values. The corresponding heat-transfer correlations for laminar flow have $Ra^{1/4}$ dependence. Bower and Saylor [12] also noted the similarity of their correlation with turbulent-flow heat-transfer despite important differences in boundary conditions and length scales. Collectively, these results may suggest that natural-convection flow under combined mass and heat transfer remains turbulent at low Ra where heat transfer alone produces laminar flow. Given that well-startup conditions on Mars would occur at low Ra , a future study will investigate this regime in more detail as part of follow-up tests.

Heat Loss. The total heat loss from the water surface into the cavity, Q_t , consists of two main components: evaporation, Q_e , and convection, Q_c . That is,

$$Q_t = Q_e + Q_c \quad (20)$$

where Q_e (W) equals the evaporative mass loss, dM/dt (kg/s), times the enthalpy of evaporation near 0°C, $h_e = 2.5 \times 10^6$ J/kg. Because heat loss through the dewar walls was likely negligible, Q_t for each test was the measured average heater power. We may thus calculate Q_c from Equation (20). The dimensionless parameter for convective heat flux is Nusselt number:

$$Nu_c \equiv \frac{h_c L}{k} \quad (21)$$

where h_c (W/m°C) is the convective heat-transfer coefficient,

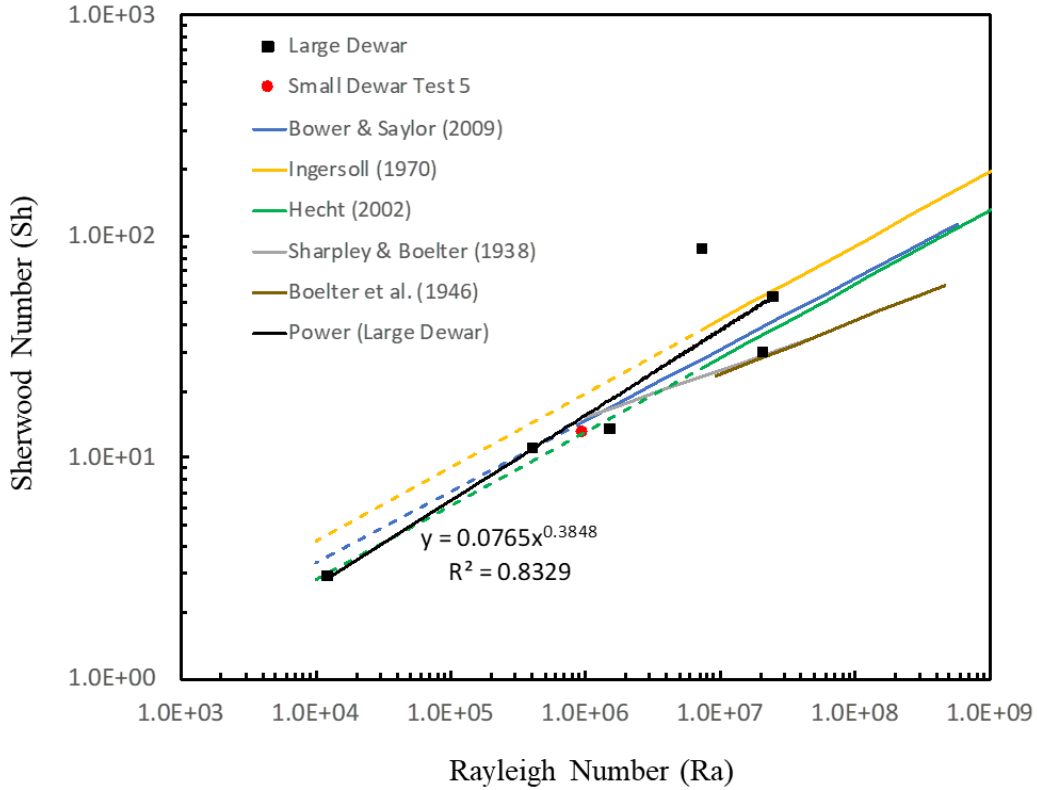


Fig. 6 Sherwood-Rayleigh correlation, $Sh(Ra)$, for test data and selected published correlations. Test 5 has little influence on the best-fit line through the large-dewar tests. The dashed lines show extensions of correlations from Bower & Saylor [12], Ingersoll [11] and Hecht [7] below their stated ranges of Ra validity to overlap with our data.

Table 2. Parameters C and n for correlation $Sh = C Ra^n$

Source	C	n	Lower Ra	Upper Ra
Large dewar tests	0.0765	0.385	1.2E+04	2.5E+07
All 7 valid tests	0.0722	0.387	1.2E+04	2.5E+07
Bower & Saylor (2009)	0.175	0.321	9.6E+05	5.7E+08
Ingersoll (1970)	0.196	0.333	8.0E+06	1.0E+11
Hecht (2002)	0.131	0.333	8.0E+06	1.0E+11
Sharpley & Boelter (1938)	0.805	0.213	1.0E+06	4.5E+07
Boelter et al. (1946)	0.491	0.241	9.3E+06	4.6E+08

$$h_c = \frac{Q_c}{A (T_s - T_a)} \quad (22)$$

and L is a characteristic length, k is thermal conductivity of the fluid, A is the effective pool area and $T_s - T_a$ is the driving temperature difference from the pool surface to the far-field atmosphere.

There are well-established correlations of $Nu_c(Ra)$ for natural-convection heat transfer over heated surfaces, and we follow the formulation presented by Holman [9]

$$Nu_c = c (Ra^*)^m \quad (23)$$

where c and m are empirical coefficients and Ra^* is defined as per Equation (8) for Ra except that Holman defines $W^* = 0.9W = L$ as the characteristic length for a horizontal circular plate. Thus $Ra^* = (0.9)^3 Ra$. As with the Bower and Saylor [12] mass-transfer correlations, Holman's heat-transfer correlations use fluid properties evaluated at the film temperature. Holman [9] presents separate expressions for laminar and turbulent natural-convection regimes:

$$\text{laminar} \quad Nu_c = 0.54 (Ra^*)^{1/4} \quad 2 \times 10^4 < Ra^* < 8 \times 10^6 \quad (24)$$

$$\text{turbulent} \quad Nu_c = 0.15 (Ra^*)^{1/3} \quad 8 \times 10^6 < Ra^* < 10^{11} \quad (24a)$$

Figure 7 shows the resulting $Nu(Ra)$ for convective and total heat losses from the pool measured during the model tests. It also shows Holman's correlations for horizontal circular plates (Equations 24 and 24a). Two key differences are apparent: the model-based Nu values are considerably higher than those for horizontal plates, and they are nearly independent of Ra . As for $Sh(Ra)$ test results, including the small-dewar Test 5 value does not appreciably change the best-fit $Nu(Ra)$ correlations.

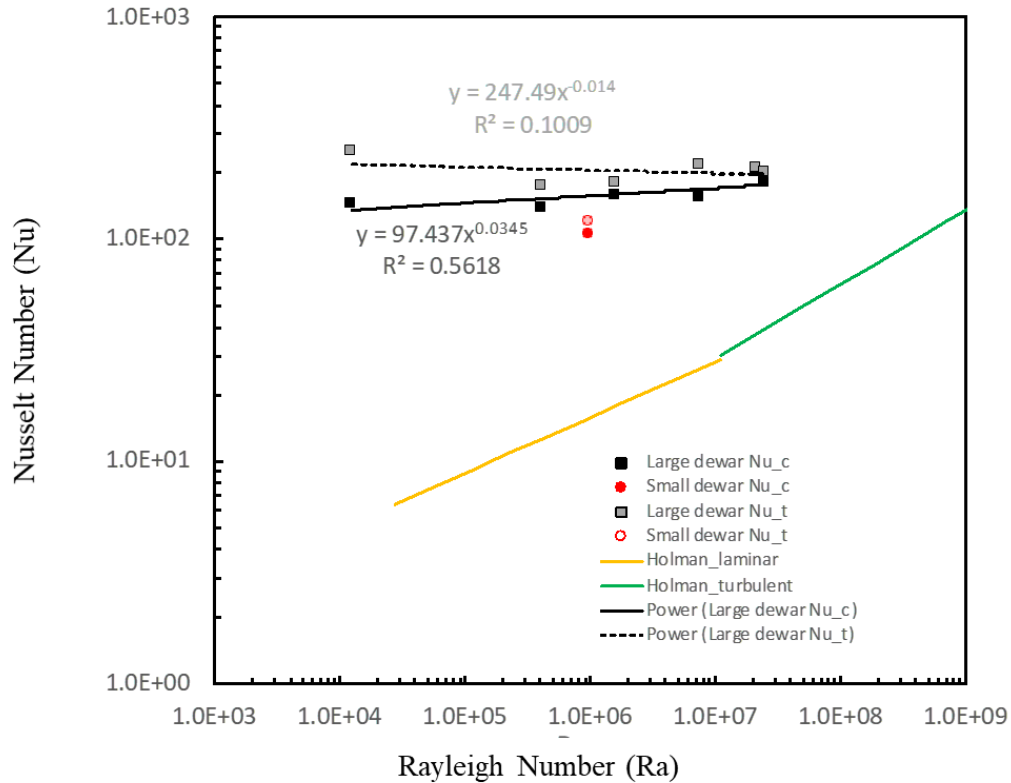


Fig. 7 Nusselt number correlation with Rayleigh number for convective, Nu_c , and total, Nu_t , heat transfer. Unlike Holman's correlations for horizontal circular plates, the model-test Nu values are nearly independent of Ra .

These high heat-transfer results warrant more investigation. However, Bower and Saylor [12] and Lunardini et al. [15] noted that mass transfer from phase change off a surface could increase mixing in the adjacent boundary layer and thereby increase the efficiency of natural-convection heat transfer. This phenomenon may account for the high $Nu(Ra)$ values obtained from the model tests, especially at low Ra where natural-convection flow is weak. Follow-on tests are planned to confirm these higher heat-transfer rates.

Recommended heat-transfer coefficients for Mars Rodwell simulations. The model tests yielded $Nu_t \sim 2 \times 10^2$ independent of Ra (Fig. 7). Assuming these results apply across the slightly greater range of interest for Mars Rodwells ($Ra \sim 10^4 - 10^9$), the total heat transfer coefficient from the pool surface varies inversely with pool diameter, via Equation (21):

$$h_{c,t} \sim \frac{200 k}{0.9 W} \quad (25)$$

The thermal conductivity of CO_2 under Mars conditions of interest ($-60^\circ C$ to $-80^\circ C$, 8 – 10 mbar) is nearly constant at $k = 1.2 \times 10^{-2} \text{ W/mK}$. Table 3 shows the resulting predictions for the water-cavity heat transfer coefficient applicable to Mars Rodwells. The default value in the CRREL simulation model is a constant $5.7 \text{ W/m}^2\text{C}$. Our model-based results suggest that the simulation should vary the water-cavity heat transfer coefficient with pool size.

Table 3 Model-based predictions for water-cavity heat-transfer coefficients, h_{w-a} , for Mars Rodwells based on pool diameter, W .

$W \text{ (m)}$	0.1	0.3	0.5	1.0	3.0	5.0
$h_{w-a} \text{ (W/m}^2\text{C)}$	27	8.9	5.3	2.7	0.89	0.53

IX. Summary

Preliminary analyses indicate that a Rodwell could be an attractive option to produce water from massive ice deposits on Mars for use during future human missions. Even though these wells have been used successfully on terrestrial ice sheets for decades, the thermal design and operation of a Rodwell on Mars must contend with a low-pressure atmosphere that enhances evaporative mass loss, and hence heat loss, from the pool surface into the cavity above it. Guided by scaling analyses, small-scale tests have been conducted to quantify the natural-convection mass- and heat-transfer rates from a water pool into a cavity under conditions of low CO_2 pressure and temperature applicable to Mars.

Instrumentation and procedural issues limited the usable data from these tests to one small-dewar and six large-dewar tests. With regard to evaporative mass transfer, the test data are consistent with dimensionless $Sh(Ra)$ correlation developed by Bower and Saylor [12] based on lab tests of water evaporating from a pool into a large air chamber. They are also consistent with correlations derived by Ingersoll [11] and Hecht [7] based on natural-convection heat transfer. Each of these earlier correlations found $Sh \sim Ra^{1/3}$, with the $1/3^{\text{rd}}$ power characteristic of large Ra where the boundary layer over the pool surface is turbulent. It is somewhat surprising that this power-law was found to extend into a range of Ra where laminar flow would be expected.

Another surprising result was found with regard to heat transfer. Rather than following established correlations for natural-convection heat transfer over flat plates (e.g., Holman [9]), the dimensionless heat-transfer rates (Nu) were much larger and approximately independent of Ra . This suggests that mass transfer from the pool enhances convective heat transfer, possibly by enhanced mixing in the boundary layer. Although this possibility has been suggested in the literature [12, 15], if it is found to be true under these conditions it could play an important role in a Rodwell on Mars, where evaporative mass transfer is enhanced relative to terrestrial wells.

X. References

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