SAND2020-1449C
Proceedings of the 2020 28th Conference on Nuclear Engineering
Joint With the ASME 2020 Power Conference
ICONE28-POWER2020
August 2-6, 2020, Anaheim, California, USA

ICONE28-POWER2020-XXXXX

ANALYSIS OF WATER RETENTION IN ISOTHERMAL VACUUM DRYING TEST

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ABSTRACT

Validation of the extent of water removal in a dry storage system using an industrial vacuum drying procedure is needed. Water remaining in casks upon completion of vacuum drying can lead to cladding corrosion, embrittlement, and breaching, as well as fuel degradation. In order to address the lack of time-dependent industrial drying data, this study employs a vacuum drying procedure to evaluate the efficiency of water removal over time in a scaled system. Isothermal conditions are imposed to generate baseline pressure and moisture data for comparison to future tests under heated conditions. A pressure vessel was constructed to allow for the emplacement of controlled quantities of water and connections to a pumping system and instrumentation. Measurements of pressure and moisture content were obtained over time during sequential vacuum hold points, where the vacuum flow rate was throttled to draw pressures from 100 torr down to 0.7 torr. The pressure rebound, dew point, and water content were observed to eventually diminish with increasingly lower hold points, indicating a reduction in retained water.

Keywords: dry cask storage, vacuum drying, residual water, water retention, dew point, thermal-hydraulics

NOMENCLATURE

DAQ	data acquisition system
DP	dew point
MS	mass spectrometer
NPT	national pipe thread
PV	pressure vessel
RS	relative sensitivity
TC	thermocouple
VCR	vacuum coupling radiation

1. INTRODUCTION

Spent fuel assemblies are dried after interim storage in pools to ensure the removal of water in assembly cavities as a precaution against issues related to pressurization and corrosion throughout the dry storage process. Numerous water retention sites exist within the internal dry cask volume that require a specialized approach to evacuation. The removal of water and oxidizing agents contained within the cask is recommended by NUREG-1536 [1]. It is advised that the cask be evacuated to a pressure of 3 torr, isolated from the pump, and held at this pressure for at least 30 minutes in order to verify liquid water removal [2]. While guidelines exist, there is a lack of time-dependent data on water removal from the full-scale industrial drying procedure for validation.

The High Burnup Confirmatory Data project provided a broad set of data on dry cask storage for designing, modeling, and licensing purposes. In particular, in-situ pressure, gas composition, and water content measurements were obtained for the cavity gas of a commercially-licensed TN-32 cask to assess fuel performance, water retention, and industrial drying efficiency [3]. Nonetheless, validation is needed of the extent of water removal in a dry storage system using an industrial vacuum drying procedure, as operational conditions leading to incomplete drying may have potential impacts on the fuel, cladding, and other components in the system. In particular, residual water can lead to cladding corrosion, embrittlement, and breaching, as well as fuel degradation [4].

Previous studies have not provided transient moisture measurements during the vacuum drying procedure [3,5], and additional information is needed to evaluate the potential impacts of water retention on extended long-term dry storage. This report will document a small-scale vacuum drying test at ambient temperature as a preliminary demonstration in anticipation of heated tests to follow. This test will provide a control data set to compare with transient temperature effects in future investigations at temperatures encountered during drying. The objectives of the test are the following:

1. Demonstrate that a sequenced vacuum drying procedure can be implemented, where pressure measurements can confirm minimal rebound pressures after the application of several hold points.

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2. Demonstrate moisture monitoring using mass spectrometry as an advanced diagnostic.

The drying of prototypic systems includes both chemically-absorbed water (i.e. water bound to contents by chemical bonds such as hydroxides and zirconium hydrates) and physically-absorbed water (i.e. water bound by weaker adsorptive forces such as Van der Waals forces and capillary effects). However, this test is designed to focus primarily on the latter mechanism, with chemisorbed water considerations relegated to separate-effects tests.

2. MATERIALS AND METHODS

2.1 Pressure Vessel

A pressure vessel (PV) was constructed of 1 in. (2.54 cm) stainless-steel tubing with welded connections to three 1 in. Swagelok vacuum coupling radiation (VCR) pipe fittings (see Figure 1). The axial length of the PV contains a partially submersible, electrically-resistive heater rod that is centered with winglets of nichrome shim. The winglets are intended to serve as additional water retention sites within the vessel.

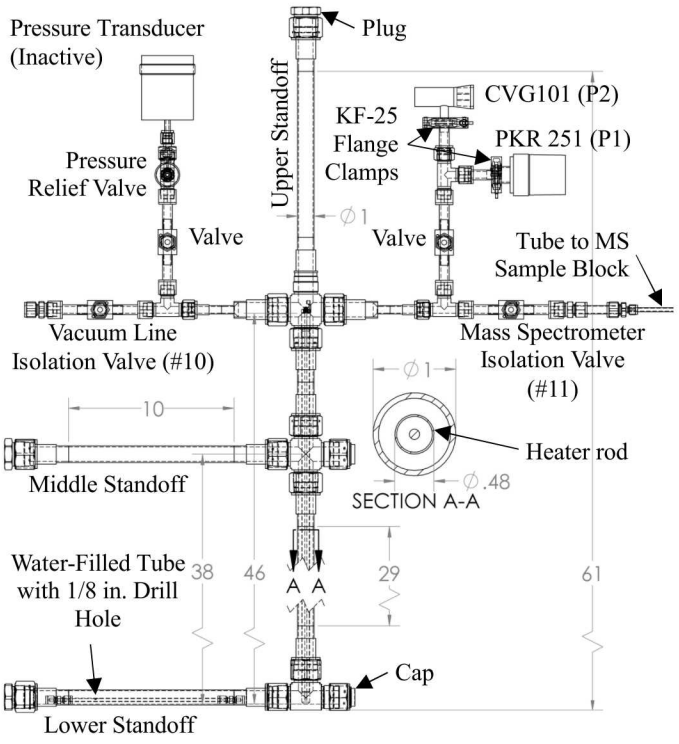

FIGURE 1: *MECHANICAL DRAWING OF PRESSURE VESSEL (DIMENSIONS IN INCHES). SECTION VIEW (A-A) HAS 5:1 PROPORTIONALITY TO THE SCALE OF THE PV.*

The design is meant to accommodate tests at both low pressures for vacuum drying and higher prototypic storage pressures (hence the inclusion of a relief valve and pressure transducer) in addition to future heated tests. Ten-inch (25.4 cm) standoffs are included for connections to electrical and thermocouple (TC) feedthroughs for those tests but were capped in this isothermal analysis. Bellows-sealed valves form the interfaces of the PV with instrumentation, a vacuum line, and a mass spectrometer (MS). The lower tee serves as the base for the heater rod and the lower standoff. The middle cross has a valve for water overflow and the middle standoff. The top cross features connections to the vacuum line, the mass spectrometer, pressure gauges, and the upper standoff.

In this isothermal study, the electrical connections and internal thermocouples were not present, but the heater was installed to maintain internal volume consistent for future tests. Nonetheless, TCs were installed to track ambient temperature and the external surface of the PV to cross-check with dew-point measurements. These included TCs at eight-inch intervals along the axial length from the base of the bottom tee upwards and at both lower and middle standoffs.

The interface with the vacuum line consists of ¼ in. (0.635 cm) copper tubing. Similarly, ¼ in. stainless steel tubing forms the connection to the mass spectrometer sample block. This sample block has its own dedicated solenoid valves that protect the sample line from overpressure. The adjoining isolation valve is opened during the test when the system is evacuated to safe pressure levels for measurement.

2.2 Pressure System

The vacuum system adjoining the PV is diagramed in Figure 2 and itemized in Table 1. It features a Varian DS-202 rotary vane pump and V-301 turbo pump operated by a solid-state controller. The needle valve is used to control the vacuum flow rate by allowing a controlled inflow from atmosphere. Two moisture-monitoring instruments are installed before the valve connection to the PV to avoid impacting leak tightness by coupling national pipe thread (NPT) connections with VCR. While this positioning prevents continuous dew point (DP) monitoring by these instruments, it allows for measurement after every vacuum hold point when the vessel is further evacuated to the next hold point. These data supplement the continuous moisture monitoring of the MS for certain pressure ranges. Due to the low quantities of water employed in this isothermal test, gas drying equipment was not installed to minimize potential leakages. However, in future tests, such a component would lie between tees #4 and #6.

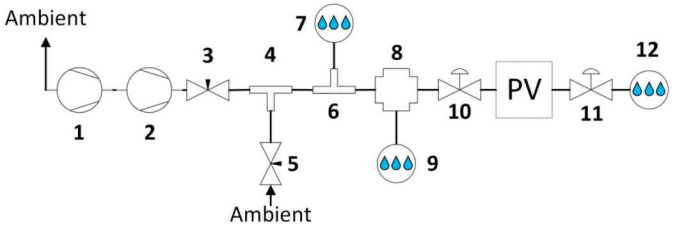

FIGURE 2: *SCHEMATIC OF VACUUM SYSTEM INTERACTING WITH PRESSURE VESSEL (SEE TABLE 1).*

Pressure is measured using a redundant combination of two gauges joined in a tee that is connected to the vessel via a valve (see upper right of Figure 1). Placement on the tee is determined by the manufacturer's required orientation. A Pfeiffer PKR 251 full-range gauge (referred to as "P1") is mounted on the middle

branch of the tee and employs a combination of a Pirani gauge and a cold cathode system for measurement. However, only the former system is active for the range of pressures applicable to this study. A Pfeiffer TPG-362 dual-channel measurement and control unit is connected to P1 and is used for both direct pressure readout and providing logarithmic analog output to the data acquisition system (DAQ). An InstruTech CVG101 Worker Bee convection Pirani gauge ("P2") was mounted on the upper branch of the tee. It is connected to an InstruTech VGC-301 vacuum gauge controller that provided direct millitorr readout and a linear analog output to the DAQ. Measurements on P1 and P2 are reproducible to ±5% and ±2% of reading, respectively, according to manufacturer specifications.

TABLE 1: *SYSTEM COMPONENTS IN FIGURE 2.*

Label	Component
1	Varian DS-202 rotary vane pump
2	Varian V-301 turbo pump
3	Vacuum pump isolation valve
4	Tubing union tee
5	Needle valve for venting
6	Female branch tee NPT to tubing
7	Omega HX200 dew point transmitter
8	Optidew sample block (upper inlet capped)
9	Optidew 401 chilled mirror hygrometer
10, 11	Bellows-sealed valve
12	Sample block of Hiden mass spectrometer

Both devices were calibrated to atmospheric conditions using local barometric pressure data (628.4 torr on the first day of testing). However, factory-calibrations of the vacuum level were not adjusted due to pump limitations. Data from all gauges and instruments were read by a common DAQ, although the mass spectrometer employed its own DAQ equipment that was later synchronized with time stamps.

2.3 Moisture Monitoring Equipment

Instrumentation on the vacuum line includes an Omega HX200 dew point transmitter and a Michel Optidew 401 chilled mirror hygrometer. Both were installed in-line with the vacuum extraction stream.

The Omega HX200 is a solid-state capacitive sensor that reacts to the activity of gaseous water. The activity is directly related to the relative humidity of moisture in the gas. With an additional measurement of the gas temperature, the relative humidity is related to the dew point temperature of the moisture in the gas. The sensor is mounted on a Swagelok tee (component #6 in Figure 2) and installed such that gas from the PV flows directly around the cylindrical probe.

A chilled mirror instrument directly measures the dew point (or frost point) temperature of a gas sample by carefully controlling the temperature of a mirror and detecting changes in surface reflectivity. The Optidew 401 has a remote sensing head that is deployed in a sample chamber fixture through which the gas sample flows. A remote temperature probe was installed outside of the vacuum line near the hygrometer for ambient temperature input.

2.4 Mass Spectrometer

A Hiden Analytical HPR-30 quadrupole mass spectrometer with a Faraday cup detector is employed to analyze transient gas concentrations in gas samples from the PV obtained via a stainless-steel capillary tube with 0.173 in. (0.439 cm) inner diameter. The HPR-30 system includes a dual-stage sampling head for measuring high-pressure samples (1-10 bar or 750-7500 torr) and low-pressure samples (0.5-5 mbar or 0.375-3.75 torr). The high-pressure sample line will be used during future forced helium dehydration tests and after the pressure vessel has been backfilled with helium (up to 8 bar or 6000 torr), while the low-pressure sample line will be used during vacuum drying tests. Data from the mass spectrometer during these two tests will be taken while the PV is within the operating pressure ranges mentioned above.

The amount of residual water detected will help define the effectiveness of the drying procedures implemented. An advantage of using an MS is that all other gaseous species are analyzed. For vacuum drying, the amount of air components can be used to evaluate the air leakage into the system. If used to monitor a commercial dry cask, an MS can also detect hydrogen generation that would indicate radiolysis or noble gas fission products (e.g. Kr-85 or Xe-137) that would indicate a leaking fuel rod.

For mass spectrometer measurements, raw counts of the two major peaks for water and the components of air (nitrogen, oxygen, and argon) were detected by the instrument. In order to obtain these counts, a gas sample from the PV was introduced into the ionization chamber, where energized electrons bombard the sample and ionize the gas molecules. The ionized molecules are filtered via a quadrupole according to the ion's mass-to-charge ratio (amu/Coulomb), which influences how each charged molecule is detected by the Faraday cup. For low reactivity molecules such as N_2, O_2, and Ar the two major ions produced are the singly- and doubly-charged molecules. These are 28 amu/C and 14 amu/C respectively for nitrogen, 32 amu/C and 16 amu/C respectively for oxygen and 40 amu/C and 20 amu/C respectively for argon. For the more reactive water molecule, the two major ions are 18 amu/C for singly-charged H_2O and 17 amu/C for the hydroxyl ion (OH^-), which is a product of water dissociation. The mass-to-charge ratios scanned do not overlap and are assumed to be unique to each target molecular species. It is further assumed that occurrence of dissociation of nitrogen and oxygen into singly-charged monoatomic species is low.

The relative concentrations of each molecule are determined by taking the ratio of the sum of the raw counts of the two major peaks of the molecule to the sum of the raw counts of all the component molecules in the PV sample.

2.5 Water Introduction

The PV is capable of being partially filled with water, where the axial filling limit corresponds to the position of the ceramic hermetic seal on the heater rod. However, in this test, a set

quantity of water is employed instead to minimize the impact of moisture on the turbo pump because no gas drying unit or water trap was installed. Deionized water was placed in a 10 in. stainless-steel tube of ¼ in. outer diameter and 0.173 in. inner diameter that was capped at both ends with Swagelok fittings. The fittings provided approximately 2 cm^3 of volume for water. The tube featured a hole of 1/8 in. (0.318 cm) diameter drilled 2 in. (5.08 cm) from one end to allow water to slowly be entrained into the PV during vacuum drying. The tube was placed into the lower standoff with the drill hole positioned upright and near the plug (see lower left of Figure 1).

Prior to introducing water, the vacuum drying procedure was conducted without the water-filled tube to provide dry baseline data on pressure and dew point. This was meant to determine the impact of leakage on pressure and the effects of ambient moisture that had entered the PV prior to testing.

2.6 Vacuum Drying Procedure

The vacuum drying procedure involves pumping the system down to specific holding pressures via a combination of controlled inflow through a needle valve (component #5 in Figure 2) and fine operation of a bellows-sealed valve on the pressure vessel (component #10). These nominal pressures are shown in Table 2, where the last holding pressure is the lowest pressure level attainable by the vacuum system (i.e. the PV is open to the full vacuum flow rate). Additional 10-minute holds at this minimum pressure are applied as-needed until the pressure rebound is deemed to be sufficiently reduced.

TABLE 2: *NOMINAL HOLD POINTS SPECIFIED FOR VACUUM DRYING.*

#	Nominal Hold Point (torr)
1	100
2	75
3	50
4	25
5	10
6	5
7	3
8	1
9	Minimum pressure

The first hold point is achieved by operating the vacuum with the needle valve fully open, such that there is no suction. The needle valve is then closed, decreasing inflow from atmospheric, until 100 torr is observed on the P1 gauge readout, upon which the PV is isolated and the needle valve is closed. The subsequent hold points are achieved by opening the bellows-sealed valve in a controlled manner, increasing suction on the PV, until the needed pressure is observed on the gauge readout.

During each hold point, the PV is isolated from the vacuum line and the pressure is held for ten-minute intervals before proceeding to the next holding pressure. This period contrasts with the thirty-minute holds used in the industrial process as part of an initial exploratory analysis. Water content is measured after each hold point with the inline dew point sensors, while gas samples are obtained continuously through the direct capillary connection to the MS for hold points below 3 torr. Pressure rebounds during a vacuum hold are monitored continuously on the DAQ.

3. RESULTS AND DISCUSSION

3.1 Pressure

Pressure data was collected for both P1 and P2 gauges and the results presented here will be averages and propagated errors of those measurements. However, it is reiterated that only the readout for P1 was referenced by the valve operator for establishing the hold point during the drying procedure. Therefore, the listed nominal hold points correspond to the targeted readout value of the P1 controller right before the PV was isolated.

The vacuum drying test was first conducted without the addition of water to the PV to collect dry baseline data. The pressure data for this test is shown in Figure 3. The measurements obtained prior to the first hold corresponded to the initial startup of the vacuum pumps and were removed from the plot. Conversely, pressure data after the last hold were included to align with the final DP readings on the HX200 and Optidew. The holding pressures are observed to be very consistent while the PV is isolated. This suggests that the system is leak-tight and relatively dry under ambient conditions. There is essentially no lag in evacuating to subsequent hold points. The minimum pressure level obtained after 1 torr was found to be 0.47 torr.

Figure 4 plots the pressure measurements for the test with the water tube installed, where the data prior to hold #1 are once again removed. It is shown that pressure begins to rebound as soon as the PV is isolated due to water boiling, and that these rebounds become more noticeable as the holding pressure is decreased. The presence of water causes lags in evacuating to subsequent hold points, which is especially obvious for hold point #7 (3 torr) where considerable time elapses before the pressure drops to hold point #8 (1 torr).

For hold point #9, the maximum vacuum level observed in the dry test could not be replicated, so the PV was isolated when a steady-state pressure of 0.98 torr was determined to be reached. Afterwards, the pressure rebounded to nearly the same maximum pressure as the previous hold point. Therefore, additional hold points were added to ensure reductions in pressure rebounds. In hold point #10 (0.75 torr) a plateau is observed in the pressure followed by a slight reduction. This may be caused by some extent of condensation of water on the interior of the PV.

The test was ended after hold point #12 when the rebound was deemed to be sufficiently low. In this hold, the average minimum pressure achieved was 0.70 torr, which is greater than the minimum pressure achieved in the dry test.

For each hold period, the minimum and maximum pressure from each gauge were used to characterize rebound behavior. Table 3 shows the average starting pressure (P_0, or the minimum pressure) of the hold points in each test and the pressure rebound (ΔP) measured during that period, where error margins are based on the two gauge measurements and related instrument errors.

ΔP is calculated from the minimum and maximum absolute pressures strictly within the holding period.

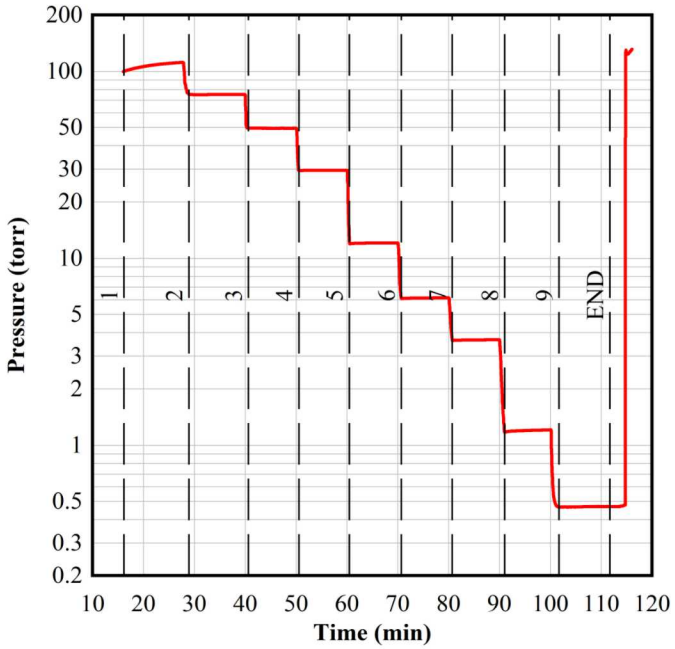

FIGURE 3: *AVERAGE PRESSURE OVER TIME FOR THE DRY TEST.*

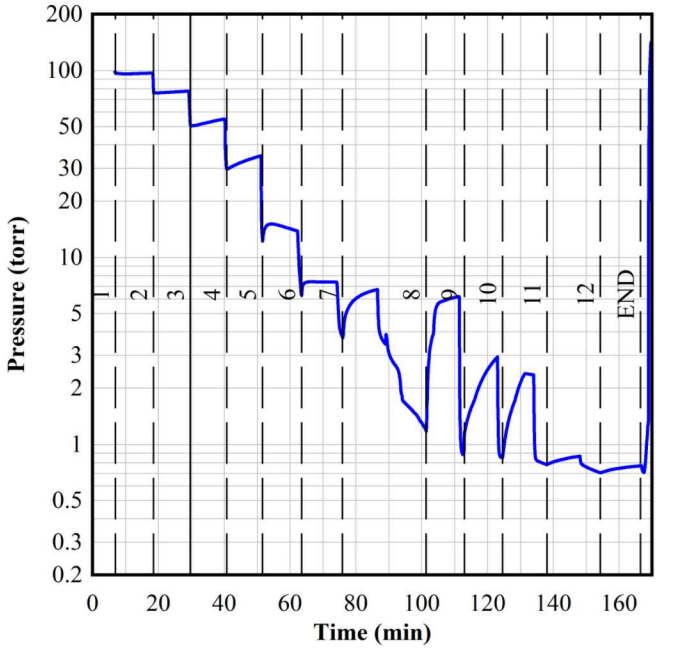

FIGURE 4: *AVERAGE PRESSURE OVER TIME FOR THE WET TEST WITH REBOUNDS DUE TO WATER BOILING.*

The large rebound for the 100 torr hold point in the dry dataset was likely caused by a leakage from the KF-25 flange on the P1, which had a rebound of 22.9 torr. This leakage decreased as the PV continued to be evacuated. (The P2 measurements were much more consistent for this hold, having a rebound of only 0.01 torr.) The flange clamp (see upper right of Figure 1) was later tightened on this instrument to avoid this effect in the wet test. The remaining dry data are more consistent and demonstrate that the pressure rebounds monotonically. The rebounds decrease as the holding pressures decrease, such that the last hold at minimum pressure has a negligibly small rebound.

The P_0 values for the wet test have strong similarity to those of the dry test. However, the ΔP values are noticeably larger per given hold point down to 1 torr. The rebound is most significant relative to P_0 in the 1 torr hold point, where pressure rises by a factor of 4.25. Afterwards, when the vacuum is run without throttling the vacuum flow rate, the pressure rebounds were less pronounced. In the last hold point, rebound is reduced to 0.07 torr over the ten-minute period.

TABLE 3: *AVERAGE STARTING PRESSURE AND AVERAGE REBOUND WITHIN TEN MINUTE HOLD POINT (UNITS IN TORR).*

Hold Point		Dry		Wet	
		P_0	ΔP	P_0	ΔP
1	100	100.±2.	12.±10.*	95.4±7.8	2.8±7.2
2	75	74.5±1.6	1.4±1.5	75.8±0.1	5.2±1.4
3	50	49.5±1.2	0.2±1.2	50.4±0.1	4.5±0.3
4	25	29.4±5.5	0.1±5.6	29.7±6.1	5.2±5.9
5	10	11.9±2.5	0.3±2.6	12.2±2.7	2.9±2.7
6	5	6.08±1.38	0.06±1.40	6.27±1.61	1.13±1.73
7	3	3.63±0.81	0.03±0.81	3.72±0.92	3.02±1.37
8	1	1.18±0.21	0.03±0.22	1.18±0.24	5.01±0.97
9+	0.98	n/a	n/a	1.13±0.20	1.80±0.50
	0.75	n/a	n/a	0.853±0.133	1.542±0.383
	0.68	n/a	n/a	0.779±0.131	0.088±0.133
	0.61	n/a	n/a	0.704±0.123	0.065±0.126
	0.41	0.466±0.065	0.005±0.067	n/a	n/a
*Leakage present in KF-25 flange of P1.					

3.2 Dew Point

The Optidew 401 dew point data collected during the dry test were considered inaccurate due to a fixed temperature feedback value of 18.70°C, so baseline data is restricted to the HX200. This issue was fixed when real-time ambient temperature (T_{amb}) feedback was employed for the wet test. Because both instruments rely on flow to provide quality measurements, the data from either sensor obtained when the PV is isolated (i.e. no vacuum flow) is not considered representative of the PV.

Figure 5 shows the dew point measurements from the two instruments for the wet test, where the spikes in the plot indicate the points in time when the PV isolation valve (component #10 in Figure 2) was opened to allow for moist gas to flow through the fittings (#6 and #8) in order to reach the next hold point. The peak dew points increase monotonically until hold point #8 is complete, upon which they begin to decrease. The peak dew

point measured after the final hold is substantially lower than that observed after the initial 100 torr hold.

Table 4 shows the peak dew points and average ambient temperatures observed for the baseline and wet tests. These values are based on the periods directly following the end of the specified hold point to the beginning of the next. The ambient temperatures for the dry test were lower than those observed in the wet test. However, given the relatively static behavior of the HX200 data in the dry test and the dynamic behavior of the wet test, the effects of retained water can be reliably verified.

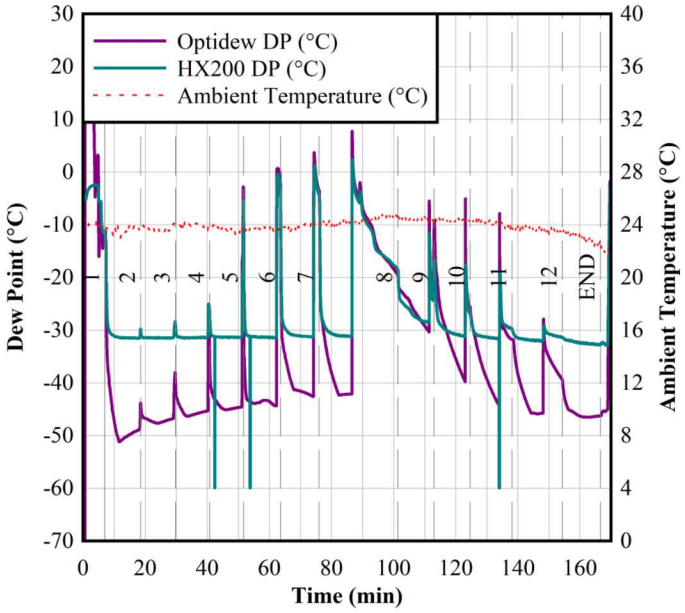

FIGURE 5: *DEW POINT MEASUREMENTS FOR THE TWO INSTRUMENTS DURING THE WET TEST.*

TABLE 4: *PEAK DEW POINTS AND AVERAGE AMBIENT TEMPERATURES (°C) AFTER SPECIFIED HOLDS.*

Hold Point	(torr)	Dry		Wet		
		DP HX200	T_{amb}	DP HX200	DP Optidew	T_{amb}
1	100	-35.5	17.6	-29.8	-43.8	23.6
2	75	-34.6	18.1	-28.3	-38.0	23.6
3	50	-36.5	18.3	-25.0	-26.4	23.9
4	25	-36.7	18.2	-5.4	-2.8	23.8
5	10	-36.7	18.3	-0.3	0.7	23.7
6	5	-36.7	17.9	1.4	3.7	23.9
7	3	-36.9	17.6	2.4	7.8	24.1
8	1	-37.2	17.5	-11.6	-5.5	24.4
9+	0.98	n/a	n/a	-17.6	-5.0	24.3
	0.75	n/a	n/a	-18.8	-7.9	24.2
	0.68	n/a	n/a	-29.1	-27.9	23.7
	0.61	n/a	n/a	-32.6	-46.2	23.0
	0.41	-38.2	17.0	n/a	n/a	n/a

The peak dew points are shown to monotonically increase up to the end the 3 torr hold point, which shows maxima of 2.4 °C and 7.8 °C from the HX200 and Optidew, respectively. Afterwards, the peak dew point decreases down to values observed after the first 100 torr hold. This corresponds to the observed pressure rebound behavior in that retained water appears to eventually decrease.

3.3 Water Content via the Mass Spectrometer

The Hiden MS was used to measure the concentrations of gases in the PV when the pressure remained below 3.6 torr. The sampling periods ranged between 1.49 to 2.28 minutes per scan. Figure 6 shows the relative concentrations of water along with nitrogen, oxygen, and argon during the low-pressure operation. Also shown is the average absolute pressure in the PV during corresponding points in time.

For the first full-vacuum hold at 1.13 torr, the pressure rose to 2.93 torr while the moisture concentration rose from 96.7 vol% to 97.1 vol% and the dew point rose from -16.4 °C to -5.7 °C (see Table 5). During the second hold at 0.85 torr, the pressure rose to 2.39 torr while the moisture concentration rose from 96.4 vol% to 96.8 vol% and the dew point rose from -19.4 °C to -8.1 °C. During the third hold at 0.78 torr, the pressure rose to 0.87 torr while the moisture concentration rose from 74.7 vol% to 76.2 vol% and the dew point rose from -22.9 °C to -21.6 °C. The final hold at 0.70 torr rose to 0.77 torr while the moisture concentration rose from 45.8 vol% to 49.3 vol% and the dew point rose from -28.9 °C to -27.4 °C.

There was a spurious shutdown of the MS sample inlet 149 minutes into the wet test. This affected one timestamp of measurements, so those points were removed from the main data. In all cases, the balance of gas was air indicating a small air leak. At the end of the test, half of the PV volume was determined to be air.

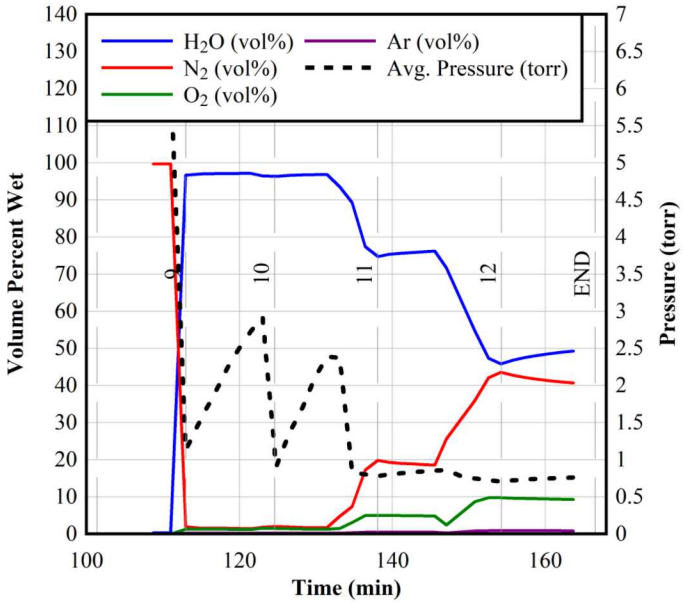

FIGURE 6: *WATER CONTENT MEASUREMENTS FROM THE MASS SPECTROMETER DURING THE WET TEST.*

TABLE 5: *MASS SPECTROMETER MEASUREMENTS DURING THE FULL-VACUUM HOLD POINTS OF THE WET TEST.*

Holding Pressure Range (torr)	Water content (vol%)	Dew Point (°C)
1.13 to 2.93	96.7 to 97.1	-16.4 to -5.7
0.85 to 2.39	96.4 to 96.8	-19.4 to -8.1
0.78 to 0.87	74.7 to 76.2	-22.9 to -21.6
0.70 to 0.77	45.8 to 49.3	-28.9 to -27.3

4. CONCLUSION

The isothermal test has indicated that pressure rebounds eventually diminish with increasingly lower hold points during the vacuum drying process. Water content measurements via dew point sensors and a mass spectrometer indicated reductions in fluid remaining in the pressure vessel. Considering the low rise in pressure and correspondingly low dew point in the final evacuation step, water content in the PV was confirmed to be significantly reduced. Therefore, the procedure used in this test can be applied to further investigations of water retention under heated conditions.

The next test will be conducted with the heater rod energized to simulated decay heat loads to reproduce thermal gradients of interest. Internal temperature measurement will allow for peak cladding temperature analyses that would be directly applicable to investigations of fuel clad integrity during the vacuum drying process. Furthermore, a longer holding period of thirty minutes can be employed to emulate the industrial procedure. When physisorbed water is sufficiently characterized, separate-effects tests can be conducted to investigate the relative magnitude of chemisorbed water on this small scale.

The vacuum system will be improved by adding a gas drying unit to handle larger quantities of water, such that a bulk filling and drainage procedure can be employed in the PV as opposed to using a small tube of water. Measurements of dew point can be expanded by installing an additional sensor with a direct VCR connection to the PV. This will allow for continuous dew point monitoring apart from the flow-through measurements obtained after the hold point and avoid gaps in the dew point data while the PV is isolated.

Implementation of the mass spectrometer can be improved if the sample block is reconfigured to cover the broader range of pressures in the test. This would require adjustments to the series of dedicated solenoid valves interacting with the PV sample. Based on the results, the lower range of pressures amenable to the system does not cover the largest fluctuations in water content. Therefore, providing water content data for the region between 1 and 10 torr would be beneficial.

Ultimately, when this series of small-scale tests is complete, the experimental procedures can be extended to tests at prototypic length. Multiple prototypic-length partially-submersible heater rods can be joined in assemblies to evaluate vacuum drying efficiency with an increased number of retention sites. Given the performance of the water tubes in this test, special fuel rod surrogates can also be tested with machined breaches and individual internal pressure monitoring equipment to expand the breadth of transient pressure data and further improve understanding of prototypic drying processes.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Department of Energy, Office of Nuclear Energy Spent Fuel and Waste Disposition Research and Development Program.

The authors would like to acknowledge the hard work and commitment of all contributors to the project. In particular, we would like to acknowledge the strong support and leadership of Ned Larson at the Department of Energy. Sylvia Saltzstein and Geoff Freeze are to be commended for their programmatic and technical guidance.

The authors would also like to thank Greg Koenig, Kyle Tsosie, Adrian Perales, and Ronald Williams III for their tireless efforts and dedication to service, which made the success of this project possible.

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