# Accuracy and error in measuring residual water mass quantity in spent nuclear fuel canisters after vacuum drying

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## 1. Introduction

Residual water present within the canister of spent nuclear fuel (SNF) storage systems can potentially exert detrimental effects on the fuel, cladding, and various other components of the system, resulting in fuel degradation, cladding corrosion, embrittlement, and eventual failure [1-3]. The NRC-02-07-C-006 report [4-5] highlights that if the vacuum drying process is expedited excessively, confined water pockets may transition into ice. The formation of ice can cause the system pressure to satisfy technical specifications despite the persistence of water within the canister. The vacuum drying test plan evaluates four essential components required for assessment: the vacuum drying system, test canister, test fuel assembly, and measurement and sensing equipment. The measurement and sensing equipment, which typically are not standard parts of industrial vacuum drying systems, are designed specifically to quantify residual water inside the canister. These include parameters such as water mass balance, water vapor content in the vacuum chamber, pressure, mass flow, and temperature. Furthermore, the report advises that during drying experiments, it is prudent to initially assess conditions that pose the highest likelihood of residual water and subsequently conduct drying experiments based on such results.

The SAND2020-5341R report [6] elaborates on testing methodologies and the development of measurement equipment aimed at verifying measurement accuracy under quantifiable conditions mirroring industrial drying operations, to support the technical basis for the long-term safe storage of spent nuclear fuel. This report demonstrated water removal via sequential vacuum drying hold points in a small-scale pressure vessel with partially submersible heater rods. Cumulative verification of water discharge was conducted under both heated and non-heated conditions using ampoules with two distinct orifice diameters. The temperature and pressure data over time were synchronously obtained with the moisture content measurements confirmed by a mass spectrometer (model: Hiden Analytical HPR-30), and the dew point data derived from the mass spectrometer was consistent with that from moisture sensors. Notably, during vacuum drying tests, significant fluctuations occurred between 1 torr and 10 torr; however, mass spectrometer measurements could not provide intermediate range sampling for pivotal pressure rebounds and potential phase changes and were only operable below 3.75 torr.

Professor Knight's team at the University of South Carolina [7-8] has been conducting experiments on forced gas circulation drying and vacuum drying methods to achieve thorough drying of SNF for dry storage purposes. Their vacuum drying experiments adhered to the stepwise vacuum pressure reduction method recommended by NRC reports, with observed freezing at the spacer disc and siphon tube. Consequently, it is deemed critically important to accurately measure any residual water that may remain inside the canister following the vacuum drying process for the effective dry storage of SNF. In response, the authors of this study have utilized a lab-scale vacuum drying test facility to evaluate the measurement accuracy of various residual water quantification methods.

## 2. Experimental equipment and methods

### *2.1 Methods for Assessing Residual Water in Tests*

In vacuum drying tests, two primary methods are employed to evaluate residual water: an energy balance analysis and a mass balance analysis. Thus, the lab-scale vacuum drying apparatus is equipped with a measurement system to capture temperature data for energy balance analysis, and additional systems to measure vapor, mass flow, and mass for mass balance analysis [5]. The equipment constituting the established vacuum drying test measurement system is depicted in Figure 1. We utilized two distinct measurement systems to quantify residual water: (1) direct measurement capturing the mass change of residual water through a precision balance and (2) indirect measurement estimating residual water by measuring the mass discharged from the canister.

(1) Direct Measurement of Residual Water: Precision Balance: The precision balance used was a product of METTLER TOLEDO, known for its accuracy up to the third decimal place. The setup involved placing a

beaker containing water on the precision balance, which was installed inside the canister. The design and utilization of the precision balance can be seen in Figure 2. (2) Indirect Estimation of Residual Water: Using Mass Flow Meter: For the indirect quantification, a steam vortex flow meter was installed at the discharge outlet connected to the vacuum pump. This setup estimates the residual water by considering the initial mass and the mass discharged from the canister. The specific model used for the steam flow meter, as shown in Figure 2, is FD-VF-T-P. By employing these two thorough measurement systems, we can accurately quantify the residual water content within the SNF canister post-vacuum drying. This dual approach ensures meticulous monitoring and validation of the residual water, contributing to enhanced safety and efficiency in the dry storage of spent nuclear fuel.

Fig. 1. Vacuum drying test equipment.


Fig. 2. Precision balance and steam vortex flow meter.

*2.2 Test-matrix*

Evaluation of Residual Water through Cross-Checking Measurement Equipment: To accurately assess the residual water content through cross-checking measurement equipment, three distinct vacuum drying test cases were conducted, designated as S3, S5, and S7 in this study. All three test cases were carried out under uniform conditions:

- Canister Dimensions: 50 cm (Φ) × 50 cm (L) and 50 cm (Φ) × 100 cm (L)
- Vacuum Pump Capacity: 600 l/min
- Beaker Volume: 1,000 ml
- Initial Residual Water Temperature: 40 °C
- Initial Residual Water Mass: 100 g

However, the tests varied in terms of environmental conditions and hold times. S3 and S7 were conducted during the high-humidity monsoon season, whereas S5 was performed during the high-temperature summer season. During the depressurization process, each test maintained specific hold times at pressures of 500, 400, 300, 200, 100, and 50 torr. S3 and S5 had hold periods of 5 minutes, while S7 had hold periods of 1 minute. The conditions for each test case are summarized in Table I, and the difference in hold times is illustrated in Figure 3. As previously described, the direct measurement of residual water mass changes was tracked using a precision balance. Cross-checking was performed by comparing the mass change figures with the amount derived by subtracting the discharged quantity measured by the flow meter from the initial residual water mass.

Test Conditions and Parameters:
- Canister Dimensions: 50 cm (Φ) × 50 cm (L), 50 cm (Φ) × 100 cm (L)
- Vacuum Pump Capacity: 600 l/min
- Beaker Volume: 1,000 ml
- Initial Residual Water Mass: 100 g
- Initial Residual Water Temperature: 40 °C
- Weather: High-humidity monsoon season (S3, S7), high-temperature summer season (S5)
- Hold Times: 5 minutes (S3, S5), 1 minute (S7)

By utilizing these comprehensive test conditions, this study aims to ensure a rigorous cross-check of residual water measurement equipment, thereby validating the accuracy and reliability of the mass balances and energy measurement systems employed.

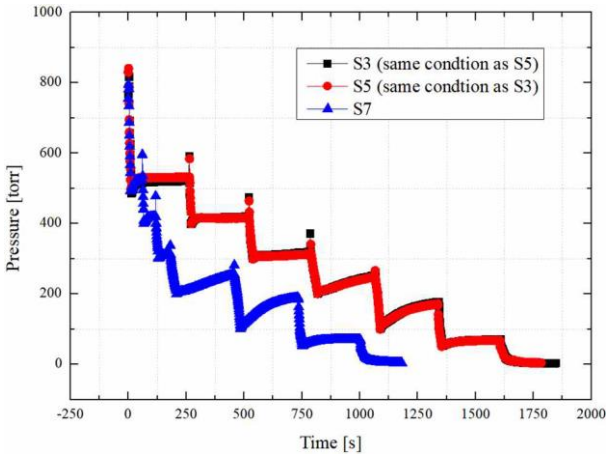


Fig. 3. Pressure variation over time for each test case.

Table I: Summary of test matrix conditions

| | Test case 3 | Test case 5 | Test case 7 |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Canister | Outer diameter: 0.5m, Height: 1m | | |
| Pump Capacity | 600L/min | | |
| Initial water condition | 40℃, 100g | | |
| Hold time | 5 min. | | 1min. |
| Weather conditions | Rainy season | Sunny day with high temp. | Rainy season |

## 3. Result and discussion

In the vacuum drying process, real-time data measurement systems enable the tracking of residual water mass and discharge flow rates. This capability allows us to observe the mass reduction trend driven by phase changes occurring during the vacuum drying process, using both measurement methods. Therefore, this report first evaluates the residual water mass change over time by comparing measurements from the precision balance and mass flow meter methods.

### *3.1 Quantification of Residual Water Over Time*

Figure 4 illustrates the change in residual water mass over time during the S3 vacuum drying test. The black data points represent direct measurements of residual water mass obtained from the precision balance, which is considered highly reliable. The mass of the residual water decreases at a consistent rate until approximately 1600 seconds, where an increase in boiling activity within the beaker accelerates the rate of mass reduction. The red data points represent the estimated residual water mass, calculated by subtracting the mass measured by the flow meter from the initial water mass of 100g. However, as shown in the figure, the estimation accuracy using the flow meter is noticeably lower than that of the precision balance. This discrepancy is attributed to the flow meter also measuring the mass of other constituents in the canister atmosphere (e.g., nitrogen), besides the water vapor. To isolate the mass of water removed, the research team utilized dew point and internal canister temperature data collected during the test. They applied the Magnus correlation, specifically the Arden Buck equation modified by Bogel for higher accuracy, to predict the relative humidity and water content in the air. This approach successfully allowed for the quantification of residual water by considering the relative humidity within the canister. The Arden Buck equation [9] used is as follows:

$$\mathrm{Ps,m(T)} = \mathrm{a}e^{(\mathrm{b}-\frac{\mathrm{T}}{\mathrm{d}})(\frac{\mathrm{T}}{\mathrm{c}+\mathrm{T}})};$$

$$\Upsilon_{\mathrm{m}}(\mathrm{T},\ \mathrm{RH}) = \ln\left(\frac{\mathrm{RH}}{100}e^{(\mathrm{b}-\frac{\mathrm{T}}{\mathrm{d}})(\frac{\mathrm{T}}{\mathrm{c}+\mathrm{T}})}\right);$$

$$\mathrm{T_{dp}} = \frac{\mathrm{c}\ln\frac{\mathrm{P_a\,(T)}}{\mathrm{a}}}{\mathrm{b}-\ln(\frac{\mathrm{P_a\,(T)}}{\mathrm{a}})} = \frac{\mathrm{c}\ln\frac{\mathrm{RH}}{100}\frac{\mathrm{P_{s,m}\,(T)}}{\mathrm{a}}}{\mathrm{b}-\ln(\frac{\mathrm{RH}}{100}\frac{\mathrm{P_{s,m}\,(T)}}{\mathrm{a}})} = \frac{\mathrm{c}\,\Upsilon_{\mathrm{m}}(\mathrm{T},\ \mathrm{RH})}{\mathrm{b}-\Upsilon_{\mathrm{m}}(\mathrm{T},\ \mathrm{RH})}$$

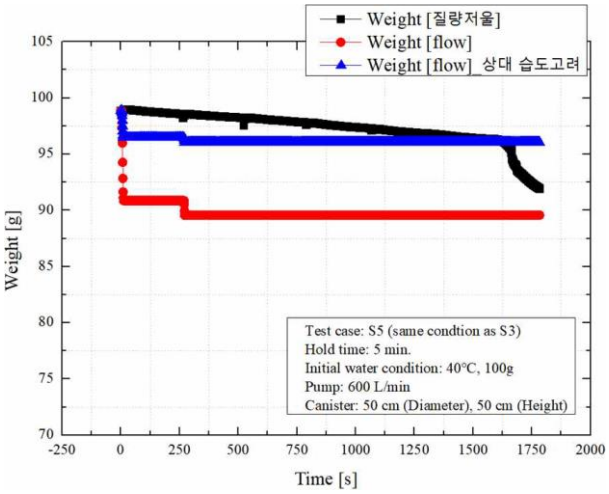


Fig. 4. Residual Water Quantification Over Time (Case: S3).

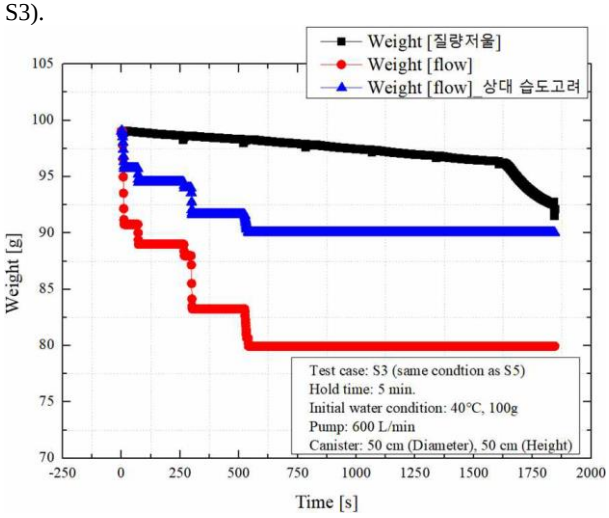


Fig. 5. Residual Water Quantification Over Time (Case: S5).

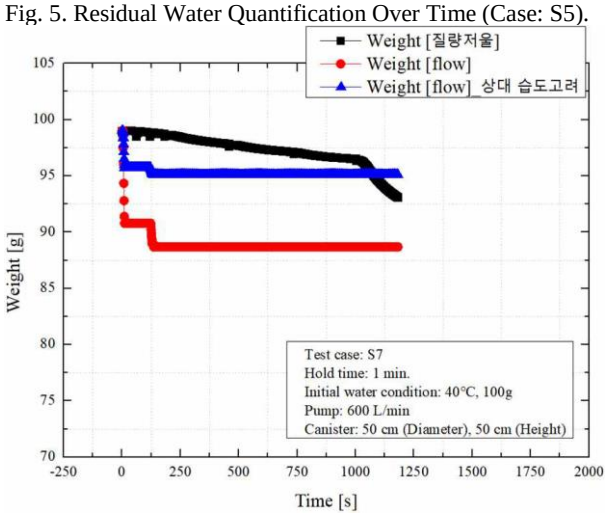


Fig. 6. Residual Water Quantification Over Time (Case: S7).

Figure 4 shows the residual water mass, adjusted for relative humidity, in blue. These data points are closer to the values obtained from the precision balance compared to the initial red data points that didn't account for dew point and relative humidity. Despite this improvement, the primary limitation of the flow meter method is its inability to reflect gradual changes

due to its detection limit, leading to sudden mass reduction events that don't provide a smooth trend like the precision balance does. Even after accounting for relative humidity and dew point, the estimations remain lower than the precision balance measurements due to the unaccounted mass of the air co-removed with the water vapor. Figures 5 and 6 depict different trends in comparison to Figure 4. While Figure 4 shows lower estimation due to the mass inclusion of air, Figures 5 and 6 show that, in cases of lower initial discharge or insufficient detection by the flow meter, the adjusted humidity-based estimates can overpredict the actual residual water mass. Two key reasons explain this discrepancy:

(1) The flow meter model FD-VF-T-P used requires a minimum flow rate to function correctly, which cannot capture the reduced water discharge as the vacuum phases progress.
(2) The accuracy of the steam flow meter decreases under low relative humidity conditions, failing to measure smaller quantities of discharged water accurately.

### *3.2 Evaluation of Residual Water Considering Dew Point Sensor and Relative Humidity*

The analysis in the previous section highlights the differences in mass change trends, which can be traced to relative humidity variations inferred from real-time dew point and canister internal temperature readings. The trend of relative humidity determined from the real-time dew point temperature values and the Arden Buck correlation is depicted in Figures 7 to 9. In the high-humidity conditions present during the monsoon season for cases S3 and S7, the initial relative humidity was around 0.7, while for case S5, it was approximately 0.4 and remained stable near this value throughout the hold periods until the end of the experiment. This indicates that the lower relative humidity conditions in the S5 case likely contributed to the steam flow meter failing to detect the lower water removal discharge rates accurately. Moreover, the shorter hold period in the S7 case (one-fifth of the duration compared to S3) likely disrupted the measurement accuracy due to the rapid decrease in pressure and relative humidity.

A detailed comparison of relative humidity changes over time and flow meter measurement points can elucidate these trends more precisely. Figure 10 compares the relative humidity changes for the evaluated test cases, while Figure 11 shows the quantity of discharged water at different time points. In the high relative humidity condition of S3, more measurement data points were recorded earlier in the experiment compared to S5 and S7. A higher relative humidity condition resulted in more comprehensive measurement data and larger recorded discharge amounts. Ultimately, the accuracy of residual water quantification using the precision balance versus the steam flow meter needs to be assessed in terms of their error margins over time, influenced by relative humidity. Therefore, the research team summarized the measurement errors for the three test cases (S3, S5, S7) under both relative humidity-considered and non-considered conditions over time.

$$\mathrm{AE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{N}} \frac{\mathrm{M_{mass-sclae}} - \mathrm{M_{flowmeter}}}{\mathrm{M_{mass-sclae}}} \times 100$$

$$\mathrm{MAE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{N}} \frac{\mathrm{ABS(M_{mass-sclae} - M_{flowmeter})}}{\mathrm{M_{mass-sclae}}} \times 100$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{N}} \left(\frac{(\mathrm{M_{mass-sclae} - M_{flowmeter}})}{\mathrm{M_{mass-sclae}}}\right)^2} \times 100$$

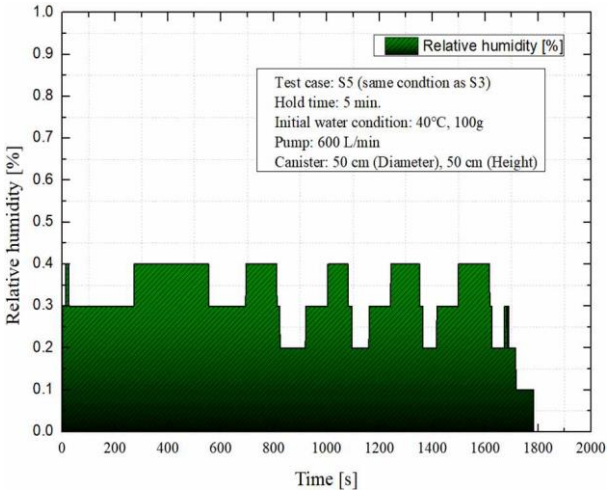


Fig. 7. Evaluation of Relative Humidity Over Time (Case: S3).

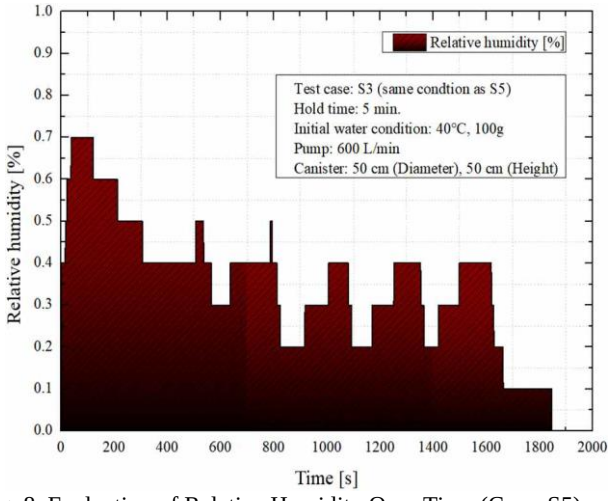


Fig. 8. Evaluation of Relative Humidity Over Time (Case: S5).

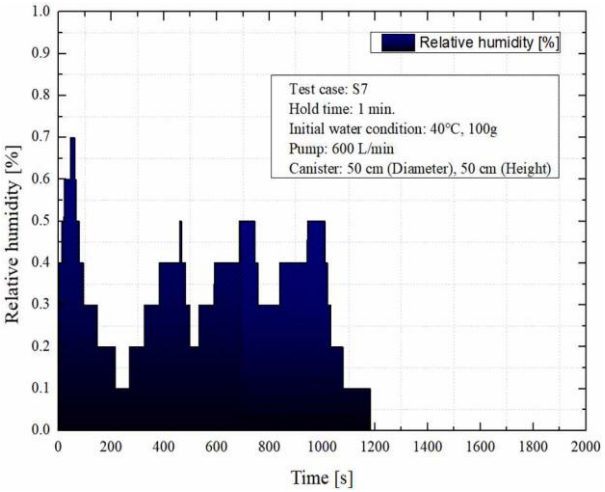


Fig. 9. Evaluation of Relative Humidity Over Time (Case: S7).

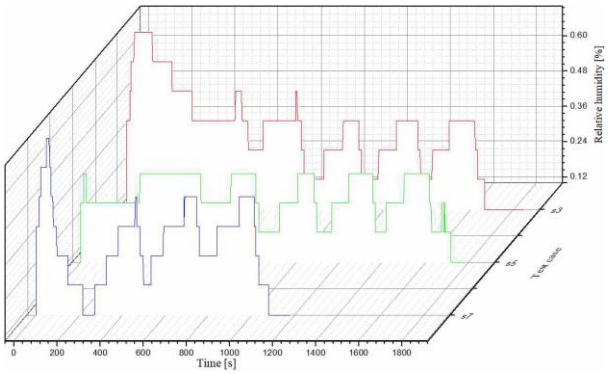


Fig. 10. Comparison of Relative Humidity Over Time (All Test Cases).

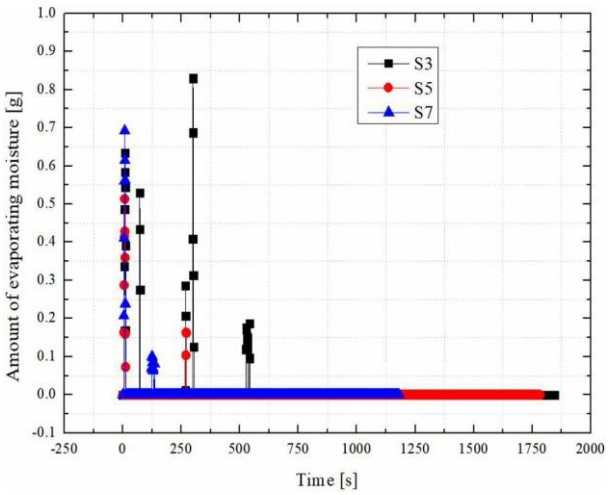


Fig. 11. Quantification of Discharged Water Over Time (All Test Cases).

### *3.3 Types of Measurement Errors Evaluated*

The results of the residual water quantification cross-check using measurement equipment are summarized in Table II. As shown in the table, the prediction accuracy improved significantly when relative humidity was taken into account compared to when it was not. Nonetheless, the influence of the canister's internal air mass, the limitations of the flow meter under different relative humidity and hold time conditions, remain unresolved. Given the impracticality of using a precision balance in actual vacuum drying, future work will focus on developing a vacuum drying mathematical model to overcome the limitations identified.

Table Ⅱ: Summary of measurement accuracy for all cases.

| | **Test case 3** | | **Test case 5** | | **Test case 7** | |
|---|---|---|---|---|---|---|
| Humidity consideration | O | X | O | X | O | X |
| AE (%) | -15.83 | -6.47 | -7.72 | -6.47 | -8.54 | -2.15 |
| MAE (%) | 15.83 | 6.47 | 7.72 | 1.69 | 8.54 | 2.37 |
| RMSE (%) | 16.14 | 6.67 | 7.84 | 1.90 | 8.65 | 2.53 |
| Max. error. | 18.69 | 8.43 | 9.15 | 4.47 | 10.29 | 3.81 |
| Min. error. | 0.04 | 0.01 | 0.10 | 0.00 | 0.11 | 0.00 |
| Error at final stage | 13.23 | 2.27 | 2.56 | 4.46 | 4.72 | 2.15 |

## 4. Conclusions

The residual water mass predicted using the steam flow meter exhibited a more than 10% error margin compared to the precision balance. However, by incorporating the Magnus relative humidity correlation and dew point data to account for humidity changes, we reduced the error margin to between 1.69% and 6.47%. The FD-VF-T-P model steam flow meter's characteristics—needing certain humidity and flow rates for accurate measurements—showed limitations in low relative humidity and high vacuum conditions, hindering precise water discharge measurements.

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