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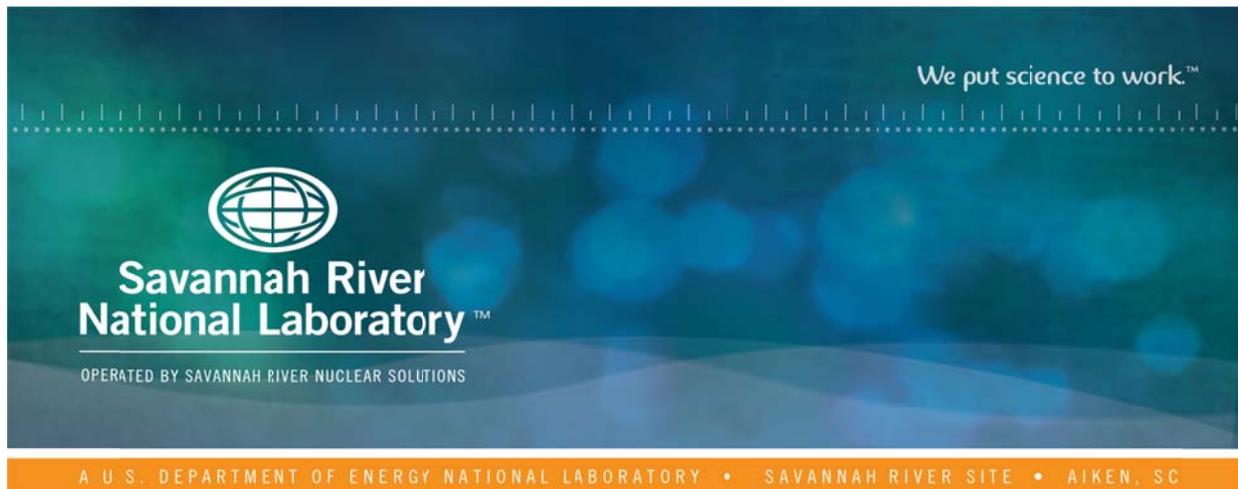
**Savannah River National Laboratory** ™

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# Technical Basis for the Reduction of the Maximum Temperature TGA-MS Analysis of Oxide Samples from the 3013 Destructive Examination Program

J. H. Scogin

March 24, 2016

SRNL-STI-2016-00126, Revision 0

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# PREFACE OR ACKNOWLEDGEMENTS

# EXECUTIVE SUMMARY

Thermogravimetric analysis with mass spectroscopy of the evolved gas (TGA-MS) is used to quantify the moisture content of materials in the 3013 destructive examination (3013 DE) surveillance program. Salts frequently present in the 3013 DE materials volatilize in the TGA and condense in the gas lines just outside the TGA furnace. The buildup of condensate can restrict the flow of purge gas and affect both the TGA operations and the mass spectrometer calibration. Removal of the condensed salts requires frequent maintenance and subsequent calibration runs to keep the moisture measurements by mass spectroscopy within acceptable limits, creating delays in processing samples.

In this report, the feasibility of determining the total moisture from TGA-MS measurements at a lower temperature is investigated. A temperature of the TGA-MS analysis which reduces the complications caused by the condensation of volatile materials is determined. Analysis shows that an excellent prediction of the presently measured total moisture value can be made using only the data generated up to 700 °C and there is a sound physical basis for this estimate.

It is recommended that the maximum temperature of the TGA-MS determination of total moisture for the 3013 DE program be reduced from 1000 ℃ to 700 ℃. It is also suggested that cumulative moisture measurements at 550 °C and 700°C be substituted for the measured value of total moisture in the 3013 DE database. Using these raw values, any of predictions of the total moisture discussed in this report can be made.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| 3013 | DOE-STD-3013-2012 |
| CI | Confidence Interval |
| DE | Destructive examination |
| MS | Mass Spectroscopy |
| SS | sum of squares |
| Stdev | Standard Deviation |
| TGA | Thermogravimetric Analysis |

## 1.0 Introduction

Thermogravimetric analysis with mass spectroscopy of the evolved gas (TGA-MS) is used to quantify the moisture content of materials in the 3013 destructive examination (3013 DE) surveillance program. The TGA measures the amount of mass lost from a sample while being heated, and the mass spectrometer (MS) can quantify the amount of moisture released from the sample. The moisture content of a sample of material is estimated by the total moisture, defined as the cumulative MS moisture measured at 85 minutes, which is the time required for the TGA to reach 1000 °C plus a short time after the end of the run.

The inventory of 3013 containers is divided into several bins or classes based on the anticipated ability to challenge the 3013 storage container. Most of the recent 3013 DE samples are from the pressure and corrosion bin and consequently have high halide salt concentrations. These halide salts have relatively high vapor pressures at elevated temperatures and readily volatilize at high end of the TGA temperature range, 1000 °C.[1,2,3] As the volatilized salts condense in the gas lines just outside the TGA furnace, they can restrict the flow of purge gas which can affect both the TGA operations and the mass spectrometer calibration.

Removal of the condensed salts requires frequent maintenance and calibration runs to keep the moisture measurements by mass spectroscopy within acceptable limits. Unfortunately, the frequent maintenance and calibration runs create delays in processing samples. During the delays in running samples, the samples can absorb moisture from the atmosphere, biasing the moisture measurement when it is finally made.

As operational delays in the TGA-MS analysis are largely a consequence of maintenance downtime and recalibration due to the volatilization of salts at high temperature, it would seem reasonable to try to reduce the downtime by operating under less severe conditions if reasonable estimates of the total moisture could be made from TGA-MS measurements at lower temperatures. This task is easily divided into two separate questions: what is the highest temperature that will minimize volatilization of salts or other condensable materials, and can the estimation of the moisture content of a sample currently made by the total moisture measurement be made using only data collected to a lower temperature?[2]

This report will discuss reducing the maximum temperature of TGA-MS analysis to reduce the complications caused by the condensation of materials which are volatile at high temperatures. The data used to develop this discussion will be the entire set of FY2014 and FY2015 TGA-MS analyses performed for the 3013 DE program. For each 3013 DE there is both initial moisture and final moisture samples run in duplicate. One initial moisture sample was run in triplicate, giving a total of 65 TGA-MS runs (Appendix B). Analysis will be presented to demonstrate that at 700 °C only a small amount of condensable material is volatilized. It will be shown that an excellent prediction of the measured total moisture value can be made using only the data generated up to 700 °C and there is a sound physical basis for this estimate.

As part of this investigation, the use of TGA measurements only was evaluated for use as predictor of total moisture. While these measurements showed some utility, the confidence interval of these predictions was six times larger than the predictions using TGA-MS data. The TGA only predictions will not be presented in this report.

1.1 Determination of a lower temperature for TGA-MS moisture measurement

For the first estimate of determining a lower temperature, the non-moisture mass loss was examined. This is calculated by subtracting the measured moisture by the MS from the total weight loss measured by the TGA at each temperature. The averaged results of this calculation for all the samples are shown in Figure 1. The dashed line is a linear fit of the averaged data from 300 °C to 700 °C. Most of the non-moisture mass loss up to 700 °C is $CO_2$ and NO and not condensable species. Since $CO_2$ and NO continue to

**Average non-moisture mass loss**
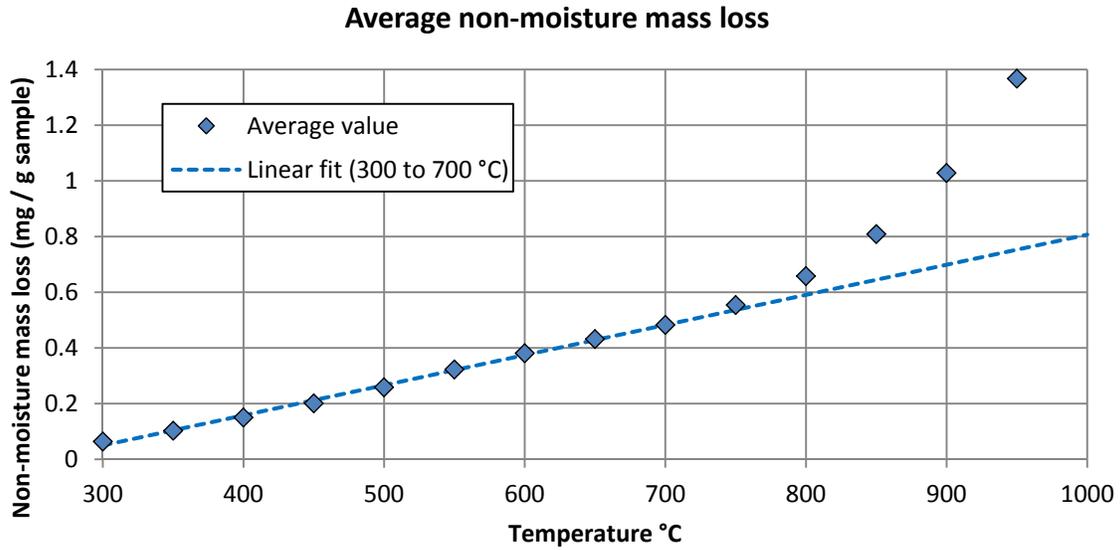


**Figure 1: Average non-moisture mass loss**

evolve throughout the entire temperature range, the amount of volatile salts is more likely to be approximated by the difference between the data points and the dashed line. It can be seen that by 800 °C, the deviation from the dashed line is clear, and there is a slight increase in generation by 750 °C.

Examining the slope of the non-moisture mass loss provides a clearer picture. As seen in Figure 2, beginning at a temperature of 700 °C, a few samples have an increase in the rate of non-moisture mass loss. By 750 °C, several samples have an increased generation rate of non-moisture mass loss.

It is important to account for the fact that after the TGA-MS has reached the target temperature; the sample temperature will continue to increase for some period of time. If the analysis were to go to 750 °C, the sample temperature might reach 775 °C before it started to cool. To avoid significant volatilization

**Slope of non-moisture mass loss**
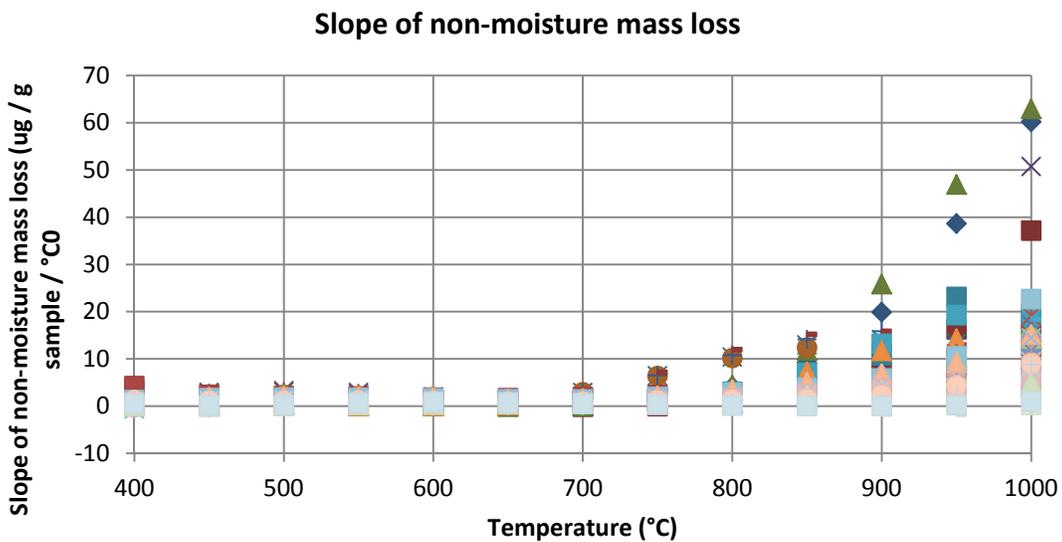


**Figure 2: Slope of non-moisture mass loss**

and subsequent condensation of non-moisture material, the TGA-MS analysis should only run to 700 °C. While most of the materials which are volatile above 700 °C are salts, any material which will condense in the gas transfer line has the potential to create instrument problems.

1.2 Prediction of total moisture from moisture data up to 700 °C

The term moisture at temperature is used to refer to the cumulative moisture (mass 18) measured by the mass spectrometer up to that temperature; e.g. the moisture at 400 °C. It should be noted that the moisture at 1000 °C is less than the total moisture, as it does not include the small amount of moisture detected by the MS between the time 1000 °C is reached and 85 minutes, and the total moisture itself is only an estimate of the moisture content of the sample.

After examining a number of potential indicators up to 700 °C, the best indicator of the total moisture was found to be cumulative moisture measured up to 700 °C. In Figure 3, the moisture at 700 °C for all measured FY2014 and FY2015 samples is plotted as a function of total moisture. (A larger version of Figure 3 is provided in Figure 11 in Appendix A.) It can be seen that moisture at 700 °C is a close approximation of the total moisture. To more clearly show the variation between the two measured values, the residuals are shown in Figure 4. The 95% confidence interval of the residuals is shown by the dashed lines.

Using the value of moisture at 700 °C with no adjustment provides a reasonable estimate of total moisture. But even with such good agreement between the moisture at 700 °C and the total moisture, it is possible to get a better prediction, which has physical meaning, of the total moisture using only the data collected up to 700 °C.

Table 1 shows the best possible fits for several different methods of predicting the total moisture from the moisture data collected up to 700 °C. Adding a constant (0.151 mg / g sample) to the moisture at 700 °C simply centers the residuals around zero and keeps the same width of the 95% confidence interval as the unadjusted data. Incremental improvements of the 95% confidence interval of the residuals are obtained by using a proportional fit and a linear fit. However, a significant reduction in the 95% confidence
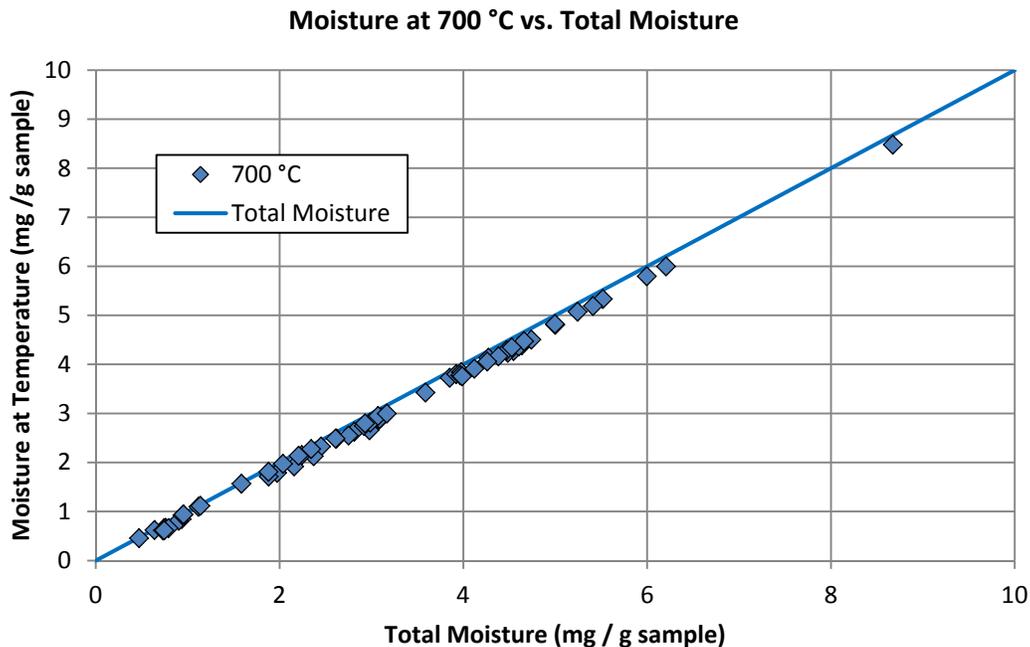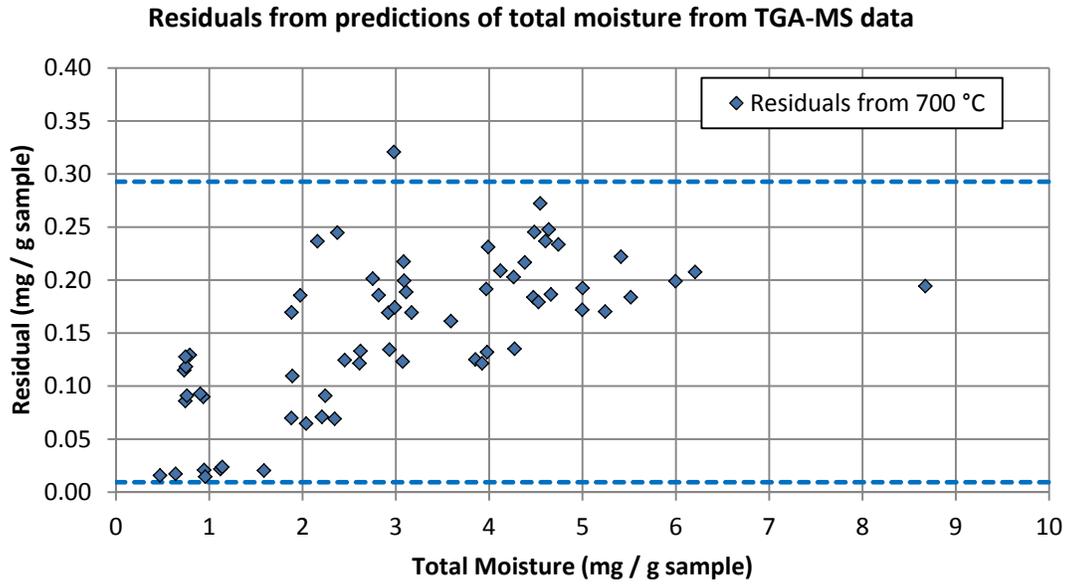


**Figure 3: Moisture at 700 °C against Total Moisture**

3

**Residuals from predictions of total moisture from TGA-MS data**



**Figure 4: Residuals of moisture at 700 °C from total moisture**

interval is found with a least squares fit using segmented moisture of two temperatures ranges, from start (around 25 °C) to 550 °C and from 550 °C to 700 °C. To determine if such additional complexity is warranted, the fit using the segmented moisture must first be shown to have a physical meaning.

A study of the intercepts of the linear fit by temperature provides insight to the physical nature of the system. Figure 5 shows the slope, intercept, and correlation coefficient for the linear fits of cumulative moisture at various temperatures to the total moisture. As expected, the slopes of the fits are greater than one, and decrease to unity as the temperature is raised and a higher percentage of the total moisture is collected. As the temperature increases, the intercepts of the linear fits at first decrease, level out between

| Best Fits | No adjustment | Constant | Proportional | Linear | Segmented |
|---|---|---|---|---|---|
| SS residual (mg / g sample)$^2$ | 1.8042 | 0.3221 | 0.2784 | 0.1951 | 0.05760 |
| Stdev of the residual (mg / g sample) | 0.1679 | 0.07095 | 0.06595 | 0.05565 | 0.03048 |
| 95% CI of the residual (mg / g sample) | +0.2928, +0.0093 | +0.1417, -0.1417 | +0.1494, -0.1142 | +0.1112, -0.1112 | +0.0609, -0.0609 |
| correlation | - | - | - | 0.9989 | 0.9997 |
| regression constant c (mg / g sample) | 0 | 0.1510 | 0 | 0.07276 | 0.07158 |
| temp 1 (°C) | 700 | 700 | 700 | 700 | Start to 550 |
| regression coefficient a | 1 | 1 | 1.0459 | 1.0269 | 0.9958 |
| temp 2 (°C) | | | | | 550 to 700 |
| regression coefficient b | | | | | 1.7581 |
| Equation for $\hat{m}$ | $m_{700}$ | $m_{700} + c$ | $a\,m_{700}$ | a $m_{700} + c$ | $a\,m_{25\,to\,550} + b\,m_{550\,to\,700} + c$ |

**Table 1 Fit statistics for moisture at temperature vs. total moisture**
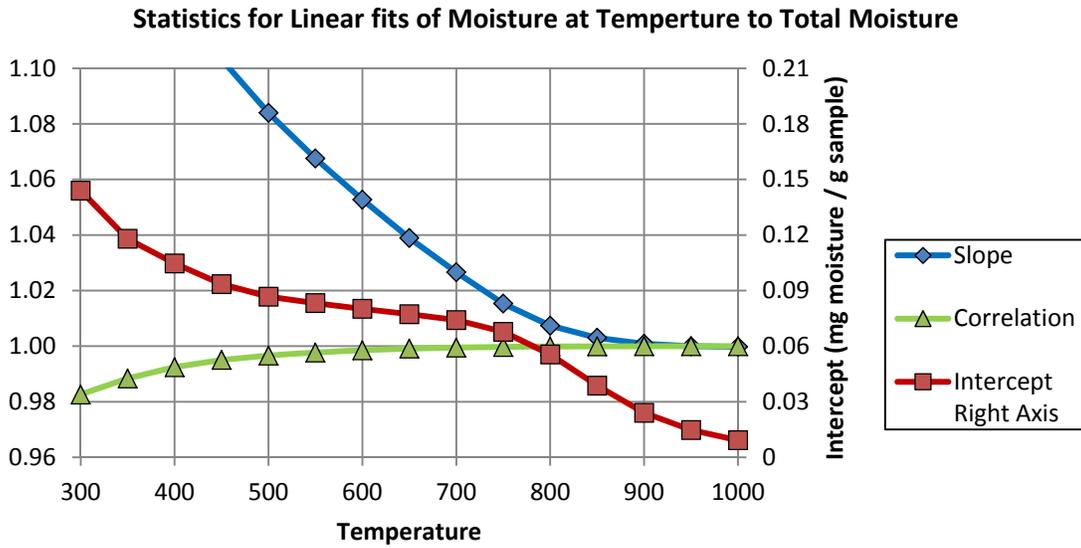
**Figure 5: Statistics from linear fit of moisture at temperature to total moisture**

500 °C and 700 °C, and then decrease again after 700 °C. The behavior of the intercepts suggests that there are two types of moisture, loosely bound and strongly bound.[4,5,6,7] The loosely bound water is mostly removed by 550 °C, the strongly bound water comes off between 700 °C and 950 °C.

This behavior is clearly shown by 14-07-IM a in Figure 6, where loosely bound moisture comes off in a large peak at 90 °C which returns to the baseline by 400 °C, and the strongly bound moisture is released in a much smaller peak between 700 ° and 950 °C. A logarithmic scale has been used so that the tightly bound moisture peak is easily seen. In this example, the tightly bound moisture is only 3.2% of the total moisture. While many other samples show similar behavior, not all samples have such clear distinction between the loosely bound and strongly bound moisture.
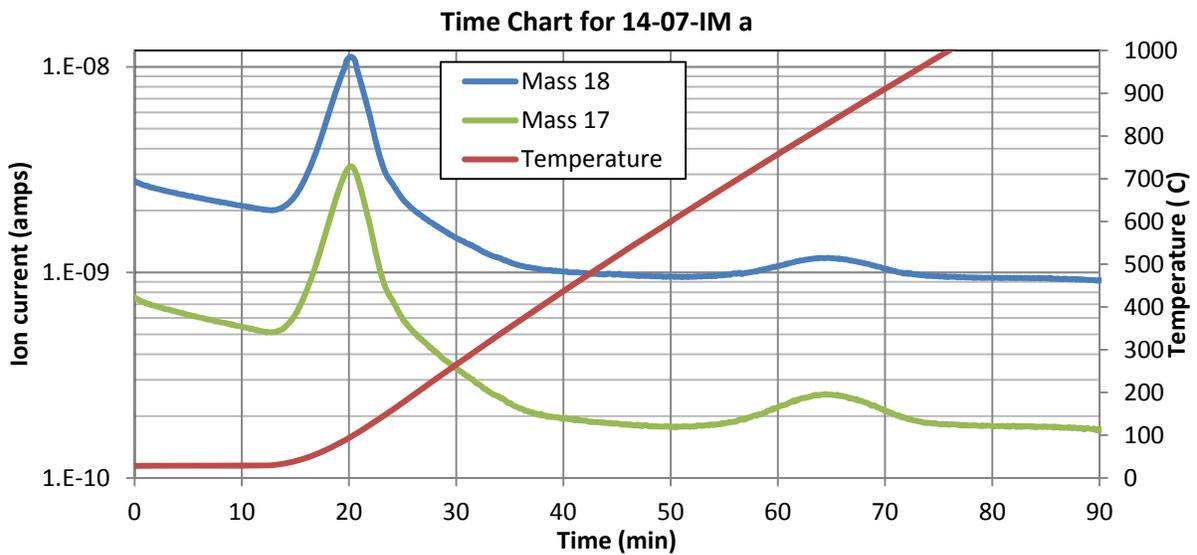


**Figure 6: TGA-MS showing loosely and strongly bound moisture**

The concept of tightly and loosely bound moisture on plutonium dioxide is widely supported in the literature. Haschke and Ricketts have proposed that the first monolayer is chemisorbed on the surface of the oxide and that succeeding monolayers are physisorbed.[8] Stakebake has shown that high purity oxide similar to 3013 material has a second region of mass loss between 700 and 1000 °C.[9] Other analyses of TGA data of Pu oxide show that small amounts of water are detected above 600 °C.[5-6] While salts are known to absorb significant amounts of moisture, the literature indicates that NaCl and KCl are largely anhydrous and that $MgCl_2$ and $CaCl_2$ are converted to oxide by 500 °C.[4, 10-13] The observed loosely bound moisture corresponds to the physisorbed moisture and the waters of hydration on the salt materials, and the strongly bound moisture corresponds to the chemisorbed moisture on the $PuO_2$ surfaces.

Understanding the two moisture types helps us interpret the regression coefficients of the segmented fit. Let us look at the fit in terms of the loosely and strongly bound moisture. The coefficient for the moisture released in the lower temperature range up to 550 °C, which corresponds to the loosely bound moisture, is almost unity (0.996), while the regression constant (0.0716 mg/g) and the datum from 550 °C to 700 °C ($1.76 * (m_{700} - m_{550})$) provide an estimate of the strongly bound moisture. The best split for the segmented data is between 550 °C and 600 °C, which is the point at which all the loosely bound moisture has been released, and the strongly bound moisture has not yet begun to come off. A graphical descption of how the segmented fit generates the predition of the total moisture is shown in Figure 7.

A graphical comparison of the unadjusted moisture at 700 °C and the segmented fit as predictors of the total moisture is shown in Figure 8. (A larger version of this plot is available as Figure 12 in Appendix A.) The residuals from the two predictions are shown in Figure 9. It is clear that the segmented fit has removed much of the scatter present in the 700 °C data. The dashed lines represent the 95% confidence interval of the residuals for each prediction. For comparison, the residuals of the linear and the segmented fit are shown in Figure 10.
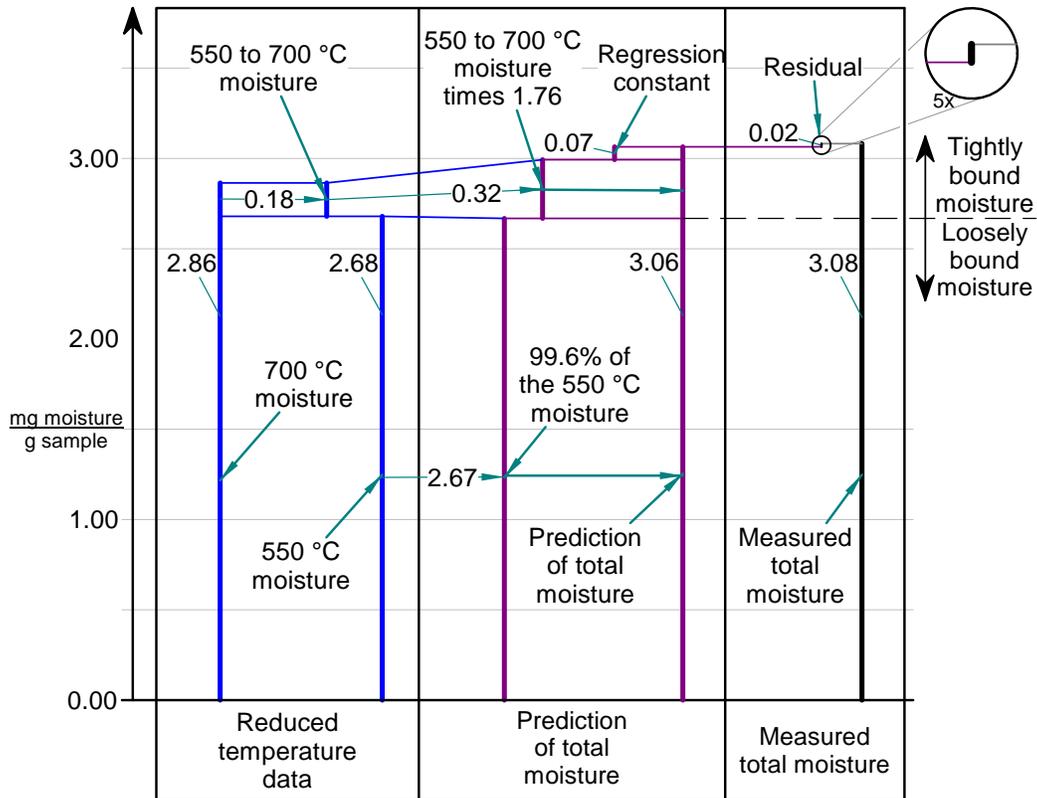


**Figure 7: Graphical description of segmented fit using data from sample 15-06 IM a**

**Moisture at 700 °C and Segmented Fit vs. Total Moisture**
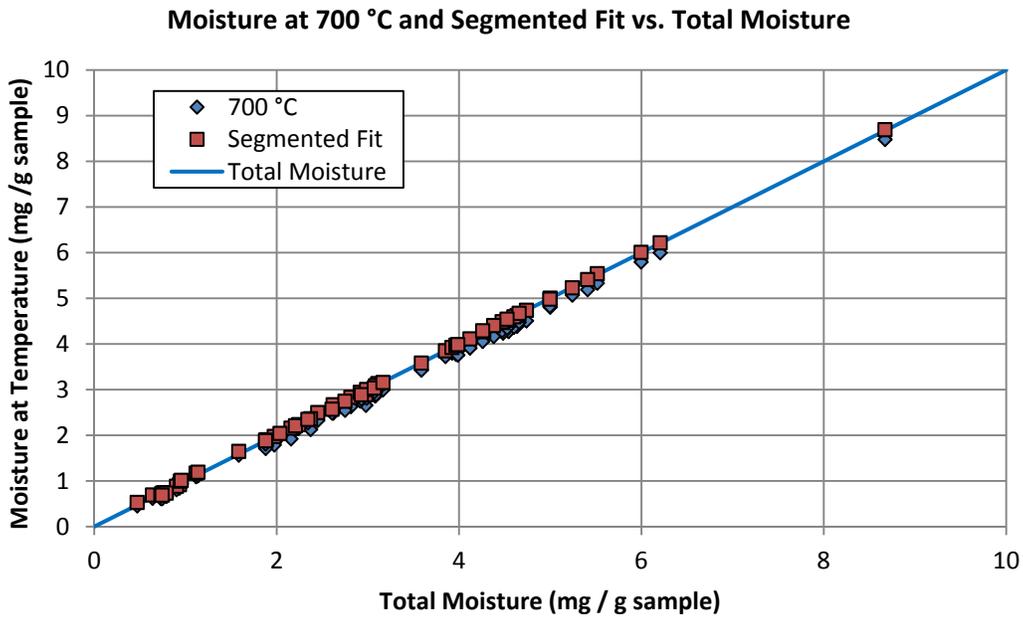


**Figure 8: Comparison of predictions of total moisture**

Using the segmented prediction, the error in the prediction of total moisture is now small when compared to the other sources of error in the measurement. It would be reasonable to assert that operating the TGA-MS up to 700 °C rather that 1000 °C has negligible effect on the ability to measure the total moisture of the sample.

**Residuals from predictions of total moisture from TGA-MS data**
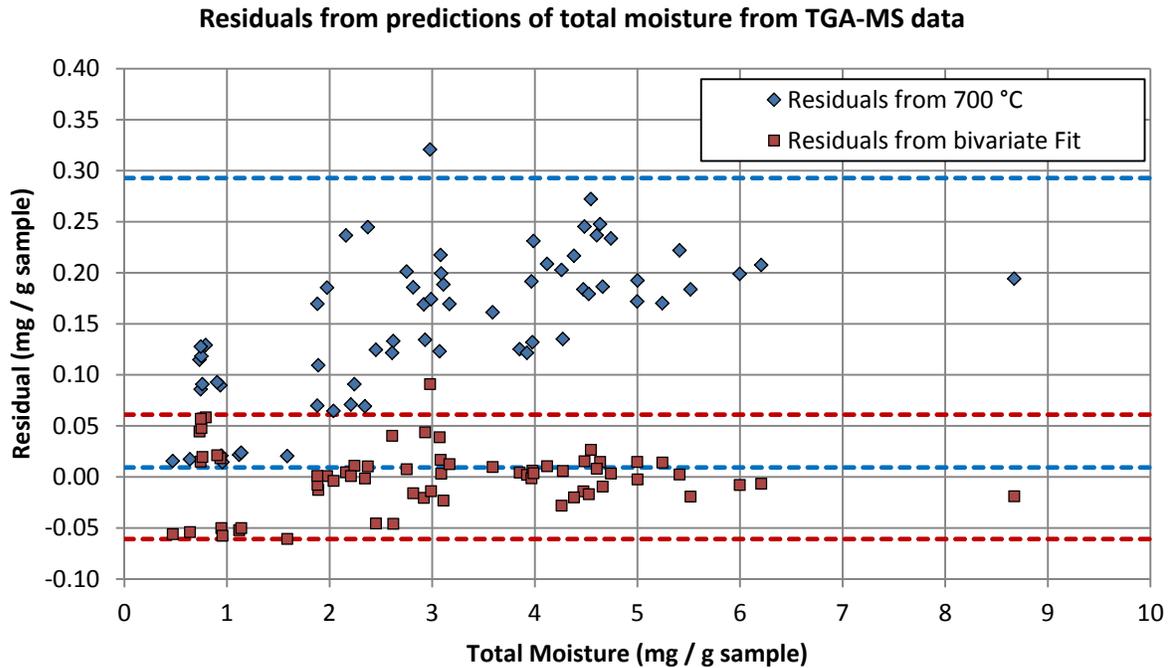


**Figure 9: Residuals from predictions of total moisture**
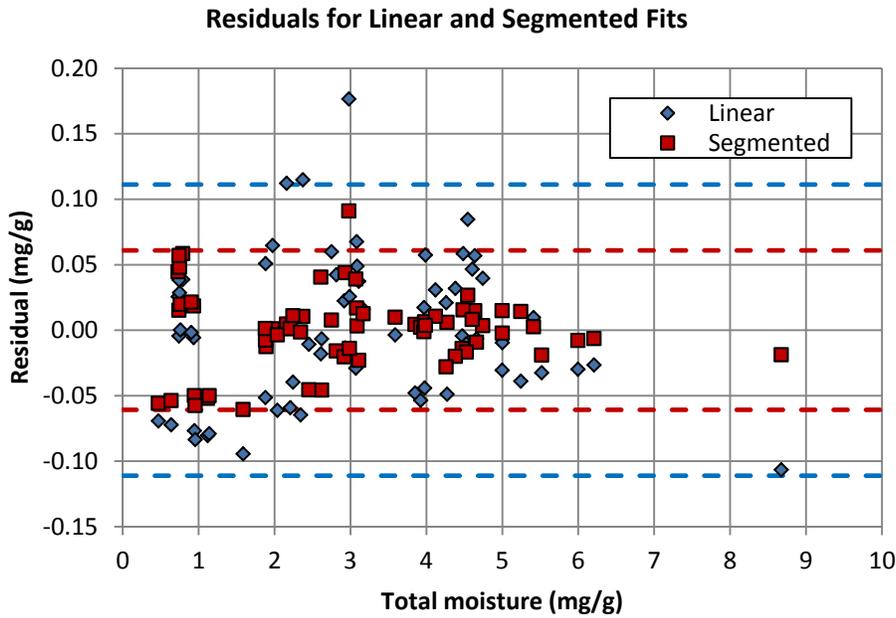
**Figure 10: Residuals from Linear and Segmented Fits**

## 2.0 Conclusions and Recommendations

Reducing the final temperature of the TGA-MS moisture determination from 1000 °C to 700 °C will reduce the volatilization of salts from the 3013 DE sample and their subsequent condensation outside the heated zone of the furnace. This in turn will reduce the time spent in maintenance and recalibration of the instruments, which will allow for more timely measurements. The reduction in temperature will result in almost no loss of precision in the total moisture measurement. The error introduced by predicting the total moisture from moisture values up to 700 °C is small compared with other uncertainties in the measurement. The 95% confidence interval of the moisture at 700 °C used as a predictor of total moisture is [+0.00093 to +0.029] weight percent. The 95% confidence interval of the segmented fit is [-0.0061 to +0.0061] weight percent, which is smaller by a factor of 2.3 and centered around zero. By comparison, the 95% confidence interval of the linear fit is [-0.011 to +0.011] weight percent.

It is recommended that the maximum temperature of the TGA-MS determination of total moisture for 3013 DE program be reduced from 1000 °C to 700 °C. It is also suggested that cumulative moisture measurements at 550 °C and 700°C be substituted for the measured value of total moisture in the 3013 DE database. Using these raw values, any of predictions of the total moisture discussed in this report can be made. After further analysis of historical data, it is possible improved predictions of the total moisture can be made using these raw values.

## 3.0 References

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## Appendix A.  Large Figures

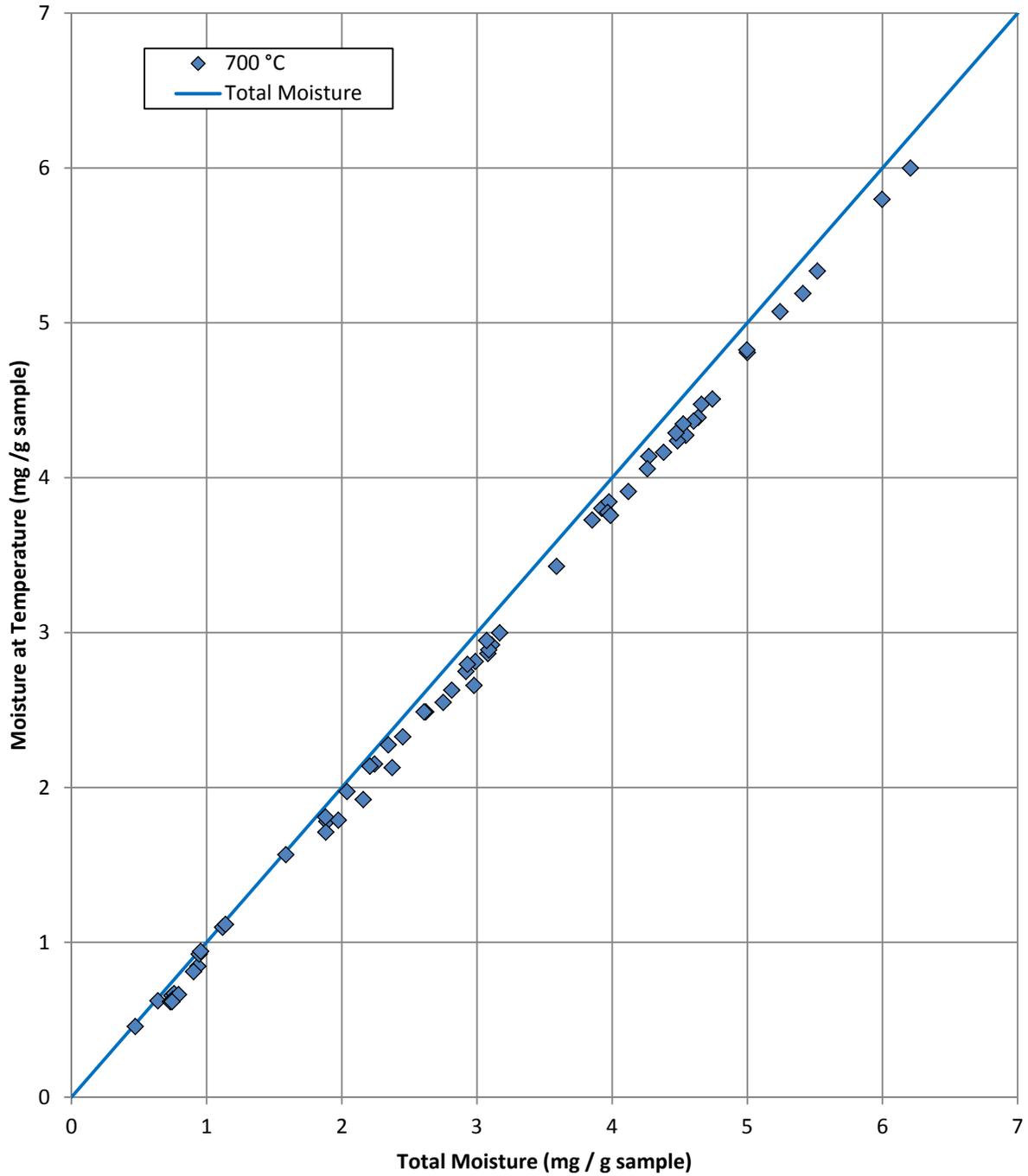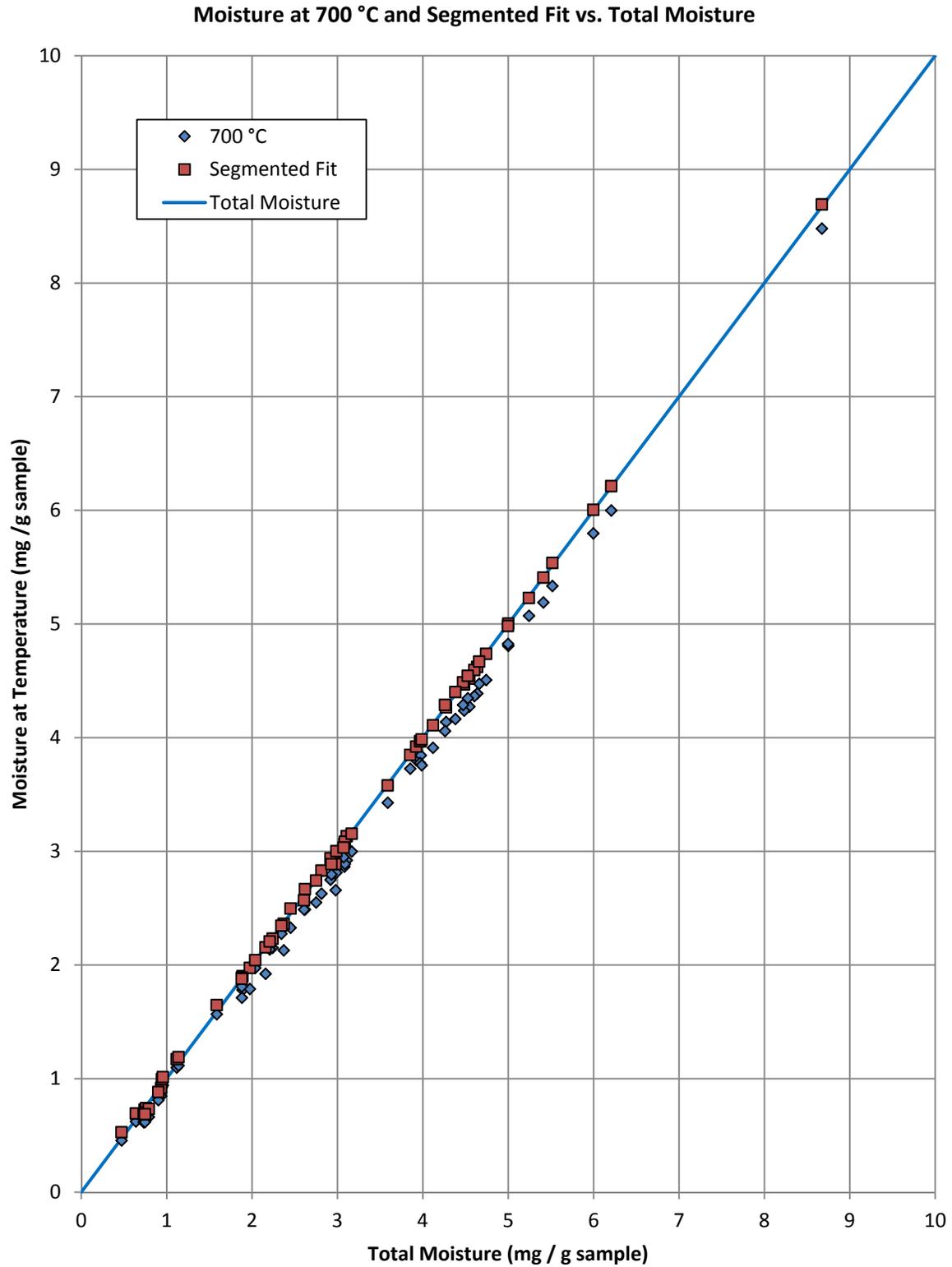**Moisture at Temperature 700 °C vs. Total Moisture**



**Figure 11:  Moisture at 700 °C vs. Total Moisture (Large Version)**

**Figure 12: Comparison of predictions of total moisture (Large Version)**

**Appendix B:  Data Summary**

| Sample ID | Date | Sample Mass (g) | Total MS Moisture (mg/g) | Calibration Factor (Area/mg) | MS Mass 18 Area | | |
|---|---|---|---|---|---|---|---|
| | | | | | 550 °C | 700 °C | Total (85 min) |
| 14-01 IM B492 a | 2015-01-22 | 2.647948 | 0.4718 | 5.09 | 6.1130 | 6.1463 | 6.3584 |
| 14-01 IM B492 b | 2015-01-22 | 2.713118 | 0.6394 | 5.09 | 8.5523 | 8.5907 | 8.8300 |
| 14-01 FM B494 a | 2015-02-18 | 2.662694 | 0.9447 | 5.09 | 12.4619 | 12.5194 | 12.8036 |
| 14-01 FM B494 b | 2015-02-18 | 2.581992 | 0.9837 | 5.09 | 12.2928 | 12.3681 | 12.9280 |
| 14-02 IM B498 a | 2015-01-15 | 3.027084 | 2.9789 | 5.09 | 37.5325 | 40.9536 | 45.8978 |
| 14-02 IM B498 b | 2015-01-15 | 3.111736 | 2.7507 | 5.09 | 37.6204 | 40.3783 | 43.5680 |
| 14-02 FM B500 a | 2015-01-16 | 2.68204 | 4.7412 | 5.09 | 58.3584 | 61.5349 | 64.7253 |
| 14-02 FM B500 b | 2015-01-16 | 2.6597 | 4.6028 | 5.09 | 55.9930 | 59.1057 | 62.3126 |
| 14-03 IM B495 a | 2015-03-10 | 2.648108 | 2.1587 | 5.09 | 22.9299 | 25.9068 | 29.0968 |
| 14-03 IM B495 b | 2015-03-10 | 2.892204 | 2.3724 | 5.09 | 28.0068 | 31.3209 | 34.9253 |
| 14-03 FM B497 a | 2015-03-12 | 2.593016 | 2.9185 | 7.35 | 49.1606 | 52.3965 | 55.6218 |
| 14-03 FM B497 b | 2015-03-12 | 2.643336 | 2.9874 | 7.35 | 51.3882 | 54.6560 | 58.0407 |
| 14-04 IM B502 a | 2015-04-10 | 2.770068 | 5.4110 | 5.66 | 77.8678 | 81.3549 | 84.8371 |
| 14-04 IM B502 b | 2015-04-10 | 2.71032 | 4.6605 | 5.66 | 65.7584 | 68.6323 | 71.4942 |
| 14-04 FM B504 a | 2015-03-18 | 2.629692 | 4.4725 | 5.66 | 61.0164 | 63.8317 | 66.5691 |
| 14-04 FM B504 b | 2015-03-18 | 2.72012 | 4.5266 | 5.66 | 64.0489 | 66.9295 | 69.6910 |
| 14-05 IM B505 a | 2015-04-20 | 2.618848 | 5.9967 | 5.66 | 82.8396 | 85.9373 | 88.8865 |
| 14-05 IM B505 b | 2015-04-20 | 2.572358 | 6.2066 | 5.443 | 80.9181 | 83.9939 | 86.9014 |
| 14-05 IM B505 c | 2015-06-18 | 1.465138 | 8.6728 | 5.443 | 65.7632 | 67.6132 | 69.1631 |
| 14-05 FM B507 a | 2015-06-18 | 2.453594 | 4.3811 | 5.443 | 52.4188 | 55.6144 | 58.5089 |
| 14-05 FM B507 b | 2015-06-23 | 2.475528 | 4.2606 | 5.443 | 51.5600 | 54.6746 | 57.4084 |
| 14-06 IM B508 a | 2015-06-23 | 2.516562 | 2.6091 | 5.5125 | 34.1452 | 34.5074 | 36.1946 |
| 14-06 IM B508 b | 2015-06-25 | 2.627426 | 2.2421 | 5.5125 | 30.8278 | 31.1561 | 32.4739 |
| 14-06 FM B510 a | 2015-06-25 | 2.503766 | 2.9299 | 5.5125 | 38.0301 | 38.5835 | 40.4392 |
| 14-06 FM B510 b | 2015-06-30 | 2.547144 | 3.0715 | 5.5125 | 40.9421 | 41.3981 | 43.1276 |
| 14-07 IM B 511 a | 2015-07-07 | 2.881236 | 1.8794 | 5.5125 | 28.6417 | 28.7392 | 29.8505 |
| 14-07 IM B511 b | 2015-07-08 | 2.797374 | 2.0381 | 5.5125 | 30.3291 | 30.4298 | 31.4279 |
| 14-07 FM B513 a | 2015-07-08 | 2.766378 | 2.2075 | 5.5125 | 32.4365 | 32.5811 | 33.6639 |
| 14-07 FM B513 b | 2014-02-11 | 2.8194 | 2.3437 | 5.5125 | 35.1774 | 35.3500 | 36.4260 |
| 14-08 IM B514 a | 2014-02-11 | 2.513136 | 3.1677 | 5.5125 | 39.7601 | 41.5363 | 43.8840 |
| 14-08 IM B514 b | 2014-02-24 | 2.603628 | 3.5886 | 5.5125 | 47.4165 | 49.1898 | 51.5058 |
| 14-08 FM B516 a | 2014-02-24 | 2.612328 | 4.9972 | 5.5125 | 67.4888 | 69.4845 | 71.9620 |
| 14-08 FM B516 b | 2014-03-05 | 2.614064 | 5.2425 | 5.5125 | 71.0930 | 73.0900 | 75.5449 |
| 14-09 IM B517 a | 2014-03-05 | 2.985772 | 0.7310 | 5.5125 | 10.1122 | 10.1402 | 12.0319 |
| 14-09 IM B517 b | 2014-03-12 | 2.918706 | 0.7507 | 5.5125 | 10.1413 | 10.1726 | 12.0784 |
| 14-09 FM B519 a | 2014-03-12 | 2.444408 | 0.7915 | 5.5125 | 8.8868 | 8.9229 | 10.6658 |
| 14-09 FM B519 b | 2014-03-25 | 2.539088 | 0.7445 | 5.5125 | 8.6021 | 8.6321 | 10.4204 |
| 15-01-IM B520 a | 2014-03-25 | 2.853118 | 1.1180 | 5.3343 | 16.5504 | 16.6846 | 17.0158 |
| 15-01-IM B520 b | 2014-04-07 | 2.956726 | 1.1391 | 5.3343 | 17.4503 | 17.5912 | 17.9654 |
| 15-01-FM B522 a | 2014-04-07 | 2.037132 | 1.8891 | 5.3343 | 18.5114 | 19.3379 | 20.5281 |
| 15-01-FM B522 b | 2014-05-08 | 2.069954 | 1.5864 | 5.3343 | 17.0613 | 17.2910 | 17.5167 |
| 15-02-IM B523 a | 2014-05-08 | 2.92472 | 0.7423 | 5.3343 | 10.1996 | 10.2391 | 11.5812 |
| 15-02-IM B523 b | 2014-05-09 | 2.81328 | 0.7595 | 5.3343 | 9.9879 | 10.0339 | 11.3982 |
| 15-02-FM B525 a | 2014-05-09 | 2.98619 | 0.9352 | 5.3343 | 13.3978 | 13.4663 | 14.8977 |

| Sample ID | Date | Sample Mass (g) | Total MS Moisture (mg/g) | Calibration Factor (Area/mg) | MS Mass 18 Area | | |
|---|---|---|---|---|---|---|---|
| | | | | | 550 °C | 700 °C | Total (85 min) |
| 15-02-FM B525 b | 2014-06-05 | 2.89975 | 0.9034 | 5.3343 | 12.4732 | 12.5380 | 13.9742 |
| 15-03-IM B526 a | 2014-06-05 | 2.565922 | 1.9743 | 5.3343 | 22.3212 | 24.4825 | 27.0227 |
| 15-03-IM B526 b | 2014-06-11 | 2.67554 | 1.8814 | 5.3343 | 22.3182 | 24.4307 | 26.8519 |
| 15-03-FM B528 a | 2014-06-09 | 2.529848 | 3.1092 | 5.3343 | 36.7143 | 39.4110 | 41.9583 |
| 15-03-FM B528 b | 2014-06-09 | 2.586092 | 2.8139 | 5.3343 | 33.7028 | 36.2540 | 38.8174 |
| 15-04-IM B529 a | 2014-06-30 | 2.427522 | 3.8518 | 5.3343 | 47.1579 | 48.2567 | 49.8778 |
| 15-04-IM B529 b | 2014-06-30 | 2.416682 | 3.9234 | 5.3343 | 47.9343 | 49.0104 | 50.5780 |
| 15-04-FM B531 a | 2014-07-02 | 2.20093 | 4.2723 | 5.3343 | 47.4192 | 48.5710 | 50.1581 |
| 15-04-FM B531 b | 2014-07-02 | 2.218606 | 3.9764 | 5.3343 | 44.4084 | 45.4966 | 47.0594 |
| 15-05-IM B532 a | 2014-07-08 | 2.360916 | 2.6207 | 5.3343 | 29.3844 | 31.3275 | 33.0041 |
| 15-05-IM B532 b | 2014-07-08 | 2.463926 | 2.4513 | 5.3343 | 28.7146 | 30.5801 | 32.2182 |
| 15-05-FM B534 a | 2014-07-14 | 2.435514 | 5.0004 | 4.2616 | 47.9501 | 49.9010 | 51.9001 |
| 15-05-FM B534 b | 2014-07-14 | 2.530026 | 5.5179 | 4.2616 | 55.3415 | 57.5118 | 59.4934 |
| 15-06-IM B536 a | 2014-07-16 | 2.537732 | 3.0815 | 4.2616 | 28.9755 | 30.9742 | 33.3260 |
| 15-06-IM B536 b | 2014-07-16 | 2.604626 | 3.0879 | 4.2616 | 30.0720 | 32.0614 | 34.2753 |
| 15-06-FM B538 a | 2014-07-21 | 2.519632 | 4.1198 | 4.2616 | 39.9822 | 41.9950 | 44.2375 |
| 15-06-FM B538 b | 2014-07-21 | 2.612054 | 3.9676 | 4.2616 | 40.0310 | 42.0313 | 44.1653 |
| 15-07-IM B539 a | 2014-07-30 | 2.47629 | 3.9877 | 4.2616 | 37.2663 | 39.6413 | 42.0819 |
| 15-07-IM B539 b | 2014-07-30 | 2.67576 | 4.5457 | 4.2616 | 45.8586 | 48.7294 | 51.8351 |
| 15-07-FM B541 a | 2014-08-05 | 2.381388 | 4.6366 | 4.2616 | 42.1510 | 44.5403 | 47.0544 |
| 15-07-FM B541 b | 2014-08-05 | 2.382418 | 4.4833 | 4.2616 | 40.6847 | 43.0274 | 45.5185 |

**Distribution:**

T. B. Brown, 773-A
D. A. Crowley, 773-43A
D. E. Dooley, 773-A
S. D. Fink, 773-A
D. T. Hobbs, 773-A
E. N. Hoffman, 999-W
F. M. Pennebaker, 773-42A
B. J. Wiedenman, 773-42A
Records Administration (EDWS)

J. M. Duffey, 773-A
M. L. Crowder, 773-A
K. P. Crapse, 773-A
F. F. Fondeur, 773-A
P. M. Almond, 773-A
D. R. Best, 772-F
J. E. Laurinat, 703-41A
N. M. Askew, 703-41A
L. E. Roy, 703-41A

B. L. Garcia-Diaz, 999-2W
K. A. Dunn, 773-41A
G. T. Chandler, 773-A
K. E. Zeigler, 773-41A

E. R. Hackney, 705-K
S. J Hensel, 705-K
B. V. Nguyen, 705-K
J. W. McClard, 703-H

L. A. Worl, LANL
T. J. Venetz, Hanford
D. C. Riley, LLNL