2. To: (Receiving Organization) Distribution		3. From: (Originating Organization) SNF Characterization Project/ 2T720		4. Related EDT No.:	
5. Proj./Prog./Dept./Div.: Spent Nuclear Fuel Project		6. Design Authority/ Design Agent/Cog. Engr.: L.A. Lawrence		7. Purchase Order No.: N/A	
8. Originator Remarks: For approval and information		11. Receiver Remarks: 11A. Design Baseline Document? ☐ Yes ☒ No		9. Equip./Component No.: N/A	
				10. System/Bldg./Facility: K Basins/100-K	
ENGINEERING DATA TRANSMITTAL				12. Major Assm. Dwg. No.: N/A	
				13. Permit/Permit Application No.: N/A	
				14. Required Response Date: N/A	

15. DATA TRANSMITTED					(F)	(G)	(H)	(I)
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Approval Designator	Reason for Trans- mittal	Originator Dispo- sition	Receiver Dispo- sition
1	HNF-1506		0	THERMAL ANALYSIS OF THERMO- GRAVIMETRIC MEASUREMENTS OF SPENT NUCLEAR FUEL OXIDATION RATES	N/A	1,3	1	

16. KEY			
Approval Designator (F)	Reason for Transmittal (G)		Disposition (H) & (I)
E, S, Q, D or N/A (see WHC-CM-3-5, Sec.12.7)	1. Approval 2. Release 3. Information	4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)	1. Approved 2. Approved w/comment 3. Disapproved w/comment 4. Reviewed no/comment 5. Reviewed w/comment 6. Receipt acknowledged

17. SIGNATURE/DISTRIBUTION (See Approval Designator for required signatures)											
(G) Reason	(H) Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN	(G) Reason	(H) Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN
		Design Authority									
		Design Agent									
1	1	Cog. Eng.	L.A. Lawrence	10-8-97	HQ-40						
1	1	Cog. Mgr.	R.P. Omberg	10-8-97	HQ-40						
		QA									
		Safety									
		Env.									
Signature of EDT Originator: L.A. Lawrence Date: 10-8-97						19. Authorized Representative Date:		20. Design Authority/ Cognizant Manager: R.P. Omberg Date: 10-8-97		21. DOE APPROVAL (if required) Ctrl. No. ☐ Approved ☐ Approved w/comments ☐ Disapproved w/comments	

THERMAL ANALYSIS OF THERMO-GRAVIMETRIC MEASUREMENTS OF SPENT NUCLEAR FUEL OXIDATION RATES

E. R. Cramer
Numatec Hanford Company, Richland, WA 99352

J. Abrefah
Pacific Northwest National Laboratory, Richland, WA 99352

EDT/ECN: 620796 UC: 2070
Org Code: 2T720 Charge Code: LB027
B&R Code: EW7040000 Total Pages: 49 ^{ew}₁₀₋₉₋₉₇

Key Words: Thermal Analysis, Thermo-Gravimetric Analysis Fuel Examinations, 105-K Basins, Spent Nuclear Fuel

Abstract: A detailed thermal analysis was completed of the sample temperatures in the Thermo-Gravimetric Analysis (TGA) system used to measure irradiated N Reactor fuel oxidation rates. Measured temperatures in the TGA are within approximately 10 °C of the actual sample temperatures and no adjustments to reported data to account for the heat input from the oxidation process are necessary.

TRADEMARK DISCLAIMER. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

Printed in the United States of America. To obtain copies of this document, contact: Document Control Services, P.O. Box 950, Mailstop H6-08, Richland WA 99352, Phone (509) 372-2420; Fax (509) 376-4989.

Christine Shillingham ^{ew}₁₀₋₉₋₉₇
Release Approval Date

Approved for Public Release

**THERMAL ANALYSIS OF THERMO-GRAVIMETRIC MEASUREMENTS
OF SPENT NUCLEAR FUEL OXIDATION RATES**

E. R. Cramer
Numatec Hanford Corporation

J. Abrefah
Pacific Northwest National Laboratory

October 1997

Document Title: THERMAL ANALYSIS OF THERMO-GRAVIMETRIC MEASUREMENTS
OF SPENT NUCLEAR FUEL OXIDATION RATES

Prepared by: 10/6/97
E. R. Cramer
Numatec Hanford Corporation Date

Prepared by: 10/7/97
J. Abrefah
Pacific Northwest National Laboratory Date

Reviewed by: 10/6/97
L. A. Lawrence
SNF Characterization Project Date

Approved by: for 10/8/97
R. P. Omberg, Manager (Acting)
SNF Characterization Project Date

Approved by: 10-7-97
S. C. Marschman, Lead Scientist
Radiomaterials Performance Team
Pacific Northwest National Laboratory Date

This page intentionally left blank.

EXECUTIVE SUMMARY

A detailed thermal analysis was completed of the sample temperatures in the Thermo-Gravimetric Analysis (TGA) system used to measure irradiated N Reactor fuel oxidation rates. Sample temperatures during the oxidation process did not show the increase which was postulated as a result of the exothermic reactions. The analysis shows the axial conduction of heat in the sample holder effectively removes the added heat and only a very small, i.e., $<10^{\circ}\text{C}$, increase in temperature is calculated. A room temperature evaporation test with water showed the sample thermocouple sensitivity to be more than adequate to account for a temperature change of approximately 5°C . Therefore, measured temperatures in the TGA are within approximately 10°C of the actual sample temperatures and no adjustments to reported data to account for the heat input from the oxidation process are necessary.

This page intentionally left blank.

CONTENTS

1.0	INTRODUCTION	7
2.0	THERMAL ANALYSIS OF THERMO-GRAVIMETRIC ANALYSIS SAMPLE TEMPERATURES	9
2.1	ADIABATIC TEMPERATURE RISE	9
2.2	FORCED CONVECTION HEAT TRANSFER	11
2.3	CONVECTION, RADIATION, AND CONDUCTION HEAT TRANSFER	11
2.4	SENSITIVITY OF CONTACT AREA	13
3.0	RESPONSE TIME OF SAMPLE THERMOCOUPLE	15
4.0	SPENT NUCLEAR FUEL OXIDATION RATE AT THE CALCULATED TEMPERATURES . .	17
5.0	WATER EVAPORATION TEST	19
6.0	REFERENCES	21
APPENDIX A	FURTHER ANALYSIS AND CONCLUSIONS RELATED TO SNFCT97:004 AND OTHER THERMO-GRAVIMETRIC ANALYSIS BASED ON OXIDATION STUDIES	A-1
APPENDIX B	CALCULATIONAL SHEETS FOR THERMAL ANALYSIS OF THERMO- GRAVIMETRIC ANALYSIS OF SAMPLE TEMPERATURES	B-1

LIST OF FIGURES

1. Schematic of the Fuel Oxidation Samples in the Thermo-Gravimetric Analysis System	10
2. Response of the Sample Thermocouple to Temperature Changes During the Water Evaporation at Ambient Condition	20

LIST OF TABLES

1. Calculated Spent Nuclear Fuel Sample Temperatures for Adiabatic Temperature Rise	22
2. Calculated Spent Nuclear Fuel Sample Temperatures for Forced Convection Analysis	22
3. Calculated Spent Nuclear Fuel Sample Temperatures for 0.5 mm Gap Under the Sample	23
4. Calculated Spent Nuclear Fuel Sample Temperatures for 1% Area Contact with Crucible	23
5. Calculated Spent Nuclear Fuel Sample Temperatures for 10% Contact with Crucible	24
6. Calculated Spent Nuclear Fuel Oxidation Rate for the Forced Convection Temperatures	25

THERMAL ANALYSIS OF THERMO-GRAVIMETRIC MEASUREMENTS OF SPENT NUCLEAR FUEL OXIDATION RATES

1.0 INTRODUCTION

The oxidation rates of N Reactor Spent Nuclear Fuel (SNF) stored in the Hanford K Basins are being measured using a Thermo-Gravimetric Analysis (TGA) system at the Pacific Northwest National Laboratory. Sample temperatures, as measured with a thermocouple positioned in the TGA adjacent to the sample container did not increase as postulated as a result of the exothermic reactions. A series of calculations conducted by R. G. Ballinger suggested actual sample temperatures may be significantly higher than the temperatures measured and reported with the corresponding oxidation data (Appendix A). A detailed thermal analysis was conducted in response to this postulated difference between actual and measured sample temperatures.

The first step in the analysis was to verify Ballinger's calculations for both the adiabatic and forced convection heat transfer models he selected. These analyses were considered to be scoping in nature and consequently a more detailed and realistic model was selected for these analysis. Actual measurements of a sample under conditions known and calculated to result in a change in sample temperatures were conducted. A measured amount of water was placed in the sample holder and the water was removed by evaporation at ambient temperatures under vacuum conditions. The results of the test showed that the decrease in temperatures due to the evaporation process was measured by the sample thermocouple, thereby establishing the sensitivity of the sample thermocouple to temperature changes.

This page intentionally left blank.

2.0 THERMAL ANALYSIS OF THERMO-GRAVIMETRIC ANALYSIS SAMPLE TEMPERATURES

A sample of SNF was placed in the TGA in a small quartz crucible that was open at the top. The crucible was placed on an alumina pedestal inside a 1.15 in. diameter furnace (Figure 1). The SNF sample was oxidized with dry air flowing through the furnace at about 250 cm³/minute.

The sample temperature was measured with a thermocouple that was held inside the alumina pedestal head, just under the crucible containing the SNF sample. This thermocouple read nearly the same as the furnace (test) temperature for all of the oxidation tests. The SNF sample thermocouple will lag rapid changes in sample temperature but will gradually approach the sample temperature exponentially with a time constant that is very fast (about 1.0 s) if the thermocouple is in good thermal contact with the SNF sample. This time constant is much longer (up to 3 minute) if the thermocouple and SNF sample are not in good thermal contact.

Heat can be transferred from the SNF sample in three ways: by convection and by radiation from the top surface and by conduction from the bottom surface. Very little heat will be removed from the sides of the sample because it is effectively insulated by stagnant air inside the crucible and also because the crucible acts as a thermal radiation shield between the sample and the furnace wall.

The results of the adiabatic calculation, forced convection model, and more detailed models considering convection, radiation, and conduction are summarized in the following sections of this report. The calculation sheets for these different models are included in Appendix B.

2.1 ADIABATIC TEMPERATURE RISE

The first analysis of the SNF sample conducted by Ballinger assumed that there is no heat transfer at all from the sample and that all of the reaction generated heat goes into raising the sample temperature (Appendix A). This assumption is not realistic but it does give an upper bound of the sample temperature.

The sample temperature rise was calculated with the following equation, where q is the reaction heat measured with the TGA system and m , C_p , and ΔT are the sample mass, heat capacity, and temperature rise.

$$q = m C_p \Delta T$$

Results of the calculations are summarized in Table 1. This initial analysis which was verified by these repeat calculations does support the contention that TGA sample temperatures could be significantly higher than the temperature reported for oxidation.

Figure 1. Schematic of the Fuel Oxidation Samples in the Thermo-Gravimetric Analysis System.

Dimensions in Inches

97080186.1

2.2 FORCED CONVECTION HEAT TRANSFER

A second analysis was performed by Ballinger which modeled the SNF sample as a sphere suspended in a gas stream flowing in a pipe. Heat transfer from the sample was calculated only for convection to the flowing air. The convective heat transfer correlation used for this analysis is:

$$Nu = 2 + (0.4 Re^{.5} + 0.06 Re^{2/3}) Pr^{.4} \left(\frac{\mu_{stream}}{\mu_{wall}} \right)^{.25}$$

where Re is the Reynolds number based on the sphere diameter, Pr is the Prandtl number, and μ_{stream} and μ_{wall} are the viscosity of the gas evaluated at the free stream temperature and the sample surface temperature respectively. For this analysis it was assumed that the free stream and wall viscosity were equal.

This was also not a realistic analysis because the SNF sample is actually in thermal contact with the alumina pedestal by conduction and with the graphite furnace wall by radiative heat transfer. Conduction to the alumina pedestal is actually quite effective because alumina has a relatively high conductivity and it acts as a fin to dissipate heat generated by the SNF sample. The radiative heat transfer is also quite effective because the graphite furnace wall has a very high emissivity.

Because the air flow rate through the furnace is very low (the average velocity is 0.02 ft/s) the SNF sample temperatures that were calculated by this analysis are not expected to be close to the actual temperatures. This analysis was however, repeated and the results compared to Ballinger (Appendix A) and the results are given in Table 2.

Temperatures were again found to be higher than the reported values and in some cases significantly higher.

2.3 CONVECTION, RADIATION, AND CONDUCTION HEAT TRANSFER

The two analyses described above, while not actually credible, did raise a valid concern that the SNF sample temperature may be significantly different from the measured temperature. More realistic analyses were then performed to determine whether this concern is really valid. These analyses were difficult to perform precisely because the exact geometry of the SNF sample, quartz crucible, and alumina pedestal is not known. But sensitivity analyses were performed and these analyses show that the actual SNF sample temperature is probably quite close to the measured temperature for most of the oxidation rate tests.

This more realistic analysis considered radiative and convective heat transfer from the top surface and conductive heat transfer from the bottom surface.

The convective heat transfer from the top surface was calculated by

$$q = hA \Delta T$$

where ΔT is the difference between the sample temperature and the gas temperature. The gas temperature was assumed to be equal to the measured furnace temperature. The convection heat transfer coefficient, h , was estimated to be 2.0 Btu/hr-ft²-F.

The radiative heat transfer from the top surface of the sample was calculated by:

$$q = AF\sigma (T_s^4 - T_F^4)$$

where F is the gray-body shape factor, σ is the Stephan-Boltzman constant, T_s is the sample temperature and T_F is the measured furnace temperature. An emissivity of 0.7 was used for the SNF surface and an emissivity of 0.98 was used for the graphite furnace wall.

The SNF sample was not cut perfectly flat and a small layer of air may have existed under the sample (Figure 1). It has been estimated that this air gap is up to 1 mm thick. Of course, some part of the bottom of the sample must be in contact with the crucible and there will be a significant amount of heat flow through that contact area.

The calculation of conduction heat transfer from the bottom surface assumed a uniform layer of air of 0.5 mm thickness between the sample and the crucible. This calculation was conservative because no credit was taken for conduction through any contact area between the sample and the crucible.

The equation to account for conduction is:

$$q = \frac{KA \Delta T}{l}$$

where K is the thermal conductivity of the air layer presumed to be under the sample and l is the air gap thickness. The thermal resistance of the quartz crucible was neglected because the conductivity of quartz is approximately 100 times that of air.

The SNF sample temperatures calculated by this method are shown in Table 3. Of the total heat transfer calculated from the sample, 9% is by convection from the top surface, 24% is by radiation from the top surface (for 300 °C test temperature), and 67% is by conduction through the air gap under the sample. These results still indicate that the SNF sample temperature is higher than the furnace temperature so more realistic assumptions than a uniform air gap are required.

2.4 SENSITIVITY OF CONTACT AREA

Because the area of contact between the SNF sample and the crucible is not known and is probably different for each sample, a sensitivity analysis was performed with variable amounts of the sample bottom surface in good contact with the crucible. The sample temperatures were calculated for 1% and 10% area contact and the resulting temperatures are given in Tables 4 and 5.

The heat flow through the contact area considered the thermal resistance of the quartz crucible over an area equal to the presumed contact area in series with a smaller thermal resistance for the SNF sample and another small resistances for the alumina pedestal. These three resistance were combined in series to get an overall conductance, U , through the contact area:

$$U = \frac{1}{\frac{I_s}{K_s A_s} + \frac{I_q}{K_q A_q} + \frac{I_a}{k_a A_a}}$$

where s, q, and a, refer to the sample, quartz crucible, and alumina pedestal. This conductance was added to the convection, radiation, and conduction heat transfer described in Section 2.3.

In the case of a 1% contact area the maximum difference between test temperatures and the calculations was approximately 40 °C with an average of approximately 15 °C. For a 10% contact area the maximum difference was reduced to approximately 10 °C with an average of less than 5 °C.

The analysis considering 10% contact between the sample and the crucible is considered to be more realistic of the actual test conditions. Therefore, actual sample temperatures are estimated to be within ± 10 °C or less of the measured values reported for the oxidation data and no adjustments to the reported data for sample temperatures are necessary.

This page intentionally left blank.

3.0 RESPONSE TIME OF SAMPLE THERMOCOUPLE

The time constant of the sample thermocouple was calculated to be 2.7 s if the thermocouple is in good thermal contact with the SNF sample. It was calculated to be 167 s if it is insulated from the sample by an air gap. The time constant is the time required for the thermocouple to reach 63% of a step change in the surface temperature of the SNF sample and is given by:

$$\tau = \frac{\rho V C_p}{hA}$$

where ρ , V , and C_p are the uranium density, volume, and heat capacity and A is the heat transfer area. The heat transfer coefficient, h , in the above equation is the effective heat transfer coefficient from the surface of the SNF sample (where the heat generation will be) to the thermocouple. The derivation of this equation can be found in any heat transfer text book.

If the thermocouple is in good thermal contact with the SNF sample, the heat transfer coefficient is the combined coefficient for the sample and the quartz crucible. If the thermocouple is not in good thermal contact, another term is included in the heat transfer coefficient for the air gap between the sample and the quartz crucible. The air gap thermal resistance is potentially much larger than the other two resistances. For this calculation it was assumed that the average thickness of the air gap was 0.5 mm.

The calculation sheets for this analysis are also included in Appendix B.

This page intentionally left blank.

4.0 SPENT NUCLEAR FUEL OXIDATION RATE AT THE CALCULATED TEMPERATURES

The kinetics of a temperature-activated reaction is strongly influenced by the accurate measurement of the sample temperature. The exothermic reaction of metallic uranium in dry air can increase the sample temperature if the heat generated by the sample is not dissipated in the experimental system. Any changes in the sample temperature, if not detected by the sample thermocouple, and consequently taken into account in the analysis can result in inaccurate comparison of the experimental data with the theoretical data. The oxidation kinetics of SNF (uranium metal) in dry air was analyzed (Abrefah 1996) with the assumption that the measured temperatures were accurate within experimental error. The measured rate constant (Abrefah 1996) was higher than the theoretical estimate based on the rate equation of Pearce et al. (Pearce 1988). This higher rate was ascribed to the characteristics of the irradiated and damaged N Reactor fuel, however, the postulated differences in measured and actual sample temperatures could account partially for the increased reactivity. Thus, the samples may have been at higher temperatures than was measured by the sample thermocouple.

The estimated temperatures calculated by Ballinger (Appendix A) were used to estimate an oxidation rate for the N Reactor fuel samples using the dry air rate equation of Pearce et al. (Pearce 1988). The calculated oxidation rates were compared to the reported experimental rates in Table 6 for the forced convection analysis.

If you assume no differences in the oxidation rates of the damaged N Reactor irradiated fuel and the literature, i.e., Pearce equation, and the temperatures calculated by Ballinger for the forced convection analysis are of the proper magnitude then there should be some level of comparison or a consistent difference between the measured and calculated oxidation rates. Comparing the measured oxidation rates to the calculated values shows in general no agreement or consistent differences (Table 6).

This comparison suggests that the temperatures calculated using the forced convection analysis do not represent the actual sample temperatures. If there was a systematic difference between the literature values of oxidation rates, i.e., Pearce equation, and the N Reactor fuel data and the calculated temperatures in general represented the sample temperatures then there would be a consistent difference or trend which was not the case for the data sets in question. The conclusion from this comparison supports the thermal analysis (Section 2.0) that sample temperatures are closer to measured temperatures than the forced convection analysis suggests.

This page intentionally left blank.

5.0 WATER EVAPORATION TEST

The TGA quartz crucible used for the SNF oxidation studies was filled with about 300 mg of water for an evaporation test at room temperature. The objective of the test was to test the responsiveness of the TGA sample thermocouple to changes in the sample temperature. The system was pumped down to initiate the evaporation of the water. The system pressure, sample temperature and weight loss due to the evaporation of the water were monitored continuously. The response of the sample thermocouple to temperature changes during the water evaporation is plotted in Figure 2 together with the weight loss. The general observations of the test are,

- The sample thermocouple decreased from ambient conditions of about 29 °C to as low as 14 °C and maintained the drop in temperature until most of the water has evaporated.
- The sample thermocouple returned to ambient temperature condition after all the water had evaporated.
- Calculations with the assumption of an adiabatic condition and averaged linear evaporation rate yielded a temperature decrease rate of about 5 °C/minute. The maximum temperature drop rate observed was about 2.4 °C/minute.

The results of the test suggest that

- Changes in the sample temperature by reaction can be detected by the TGA sample thermocouple.
- A fraction of the heat loss may be dissipated to other parts of the system through the three heat transfer processes. Radiation at these low temperatures will have negligible contribution to heat loss. The system was evacuated during the test and thus, will minimize any heat transfer mechanism by convection. Therefore, the dominant heat loss mechanism was conduction consistent with the thermal analysis (Section 2.3). The dominant heat loss mechanism for the sample is conduction down the stem of the sample holder.
- The return of the sample thermocouple to ambient conditions following the complete evaporation of the water was a demonstration of proper thermocouple behavior.

Figure 2. Response of the Sample Thermocouple to Temperature Changes During the Water Evaporation at Ambient Condition.

This page intentionally left blank.

6.0 REFERENCES

Abrefah J., H. C. Buchanan, and S. C. Marschman, 1996, *Oxidation Kinetics of K-West Spent Nuclear Fuel in Dry Air*, SNFCT97:004, Pacific Northwest National Laboratory, Richland, Washington.

Pearce, R. J., M. J. Bennet, and J. B. Price, 1988, "Oxidation of Irradiated Uranium in Moist Air," *Nuclear Energy* 27(5):305.

Table 1. Calculated Spent Nuclear Fuel Sample Temperatures for Adiabatic Temperature Rise.

TGA Run	Test Temp. (°C)	Sample Weight (g)	dW (mg)	Calculated Sample Temp. °C	
				R.G. Ballinger Results	E.R. Cramer Results
18	144	5.41	6.5 (6 min)	338	482
	144	5.41	2.5 (20 min)	273	273
23	150	3.32	0.15 (70 min)	162	162
18b	150	6.35	0.2 (5 min)	160	159
	150	6.35	0.4 (1 min)	187	168
	150	6.35	3.1 (5 min)	287	287
7	300	6.88	8 (20 min)	627	627
	300	6.88	3 (10 min)	422	422
	300	6.88	5 (25 min)	504	504
	300	6.88	7 (10 min)	586	586
21a	300	6.04	2.5 (10 min)	416	416
22	350	5.93	13 (10 min)	966	966

Table 2. Calculated Spent Nuclear Fuel Sample Temperatures for Forced Convection Analysis.

TGA Run	Test Temp. (°C)	Sample Weight (g)	dW (mg)	Calculated Sample Temp. °C	
				R.G. Ballinger Results	E.R. Cramer Results
18	144	5.41	6.5 (6 min)	238	356
	144	5.41	2.5 (20 min)	155	168
23	150	3.32	0.15 (70 min)	150	150
18b	150	6.35	0.2 (5 min)	153	158
	150	6.35	0.4 (1 min)	181	228
	150	6.35	3.1 (5 min)	191	271
7	300	6.88	8 (20 min)	342	378
	300	6.88	3 (10 min)	331	359
	300	6.88	5 (25 min)	321	339
	300	6.88	7 (10 min)	374	437
21a	300	6.04	2.5 (10 min)	320	349
22	350	5.93	13 (10 min)	455	604

Table 3. Calculated Spent Nuclear Fuel Sample Temperatures for 0.5 mm Gap Under the Sample.

TGA Run	Test Temp. (°C)	Sample Weight (g)	dW (mg)	Calculated Sample Temp. °C
18	144	5.41	6.5 (6 min)	207
	144	5.41	2.5 (20 min)	151
23	150	3.32	0.15 (70 min)	150
18b	150	6.35	0.2 (5 min)	152
	150	6.35	0.4 (1 min)	173
	150	6.35	3.1 (5 min)	186
7	300	6.88	8 (20 min)	320
	300	6.88	3 (10 min)	315
	300	6.88	5 (25 min)	310
	300	6.88	7 (10 min)	335
21a	300	6.04	2.5 (10 min)	313
22	350	5.93	13 (10 min)	409

Table 4. Calculated Spent Nuclear Fuel Sample Temperatures for 1% Area Contact with Crucible.

TGA Run	Test Temp. (°C)	Sample Weight (g)	dW (mg)	Calculated Sample Temp. °C
18	144	5.41	6.5 (6 min)	184
	144	5.41	2.5 (20 min)	149
23	150	3.32	0.15 (70 min)	150
18b	150	6.35	0.2 (5 min)	151
	150	6.35	0.4 (1 min)	165
	150	6.35	3.1 (5 min)	173
7	300	6.88	8 (20 min)	313
	300	6.88	3 (10 min)	310
	300	6.88	5 (25 min)	307
	300	6.88	7 (10 min)	323
21a	300	6.04	2.5 (10 min)	308
22	350	5.93	13 (10 min)	391

Table 5. Calculated Spent Nuclear Fuel Sample Temperatures for 10% Contact with Crucible.

TGA Run	Test Temp. (°C)	Sample Weight (g)	dW (mg)	Calculated Sample Temp. °C
18	144	5.41	6.5 (6 min)	153
	144	5.41	2.5 (20 min)	145
23	150	3.32	0.15 (70 min)	150
18b	150	6.35	0.2 (5 min)	150
	150	6.35	0.4 (1 min)	153
	150	6.35	3.1 (5 min)	155
7	300	6.88	8 (20 min)	303
	300	6.88	3 (10 min)	302
	300	6.88	5 (25 min)	302
	300	6.88	7 (10 min)	306
21a	300	6.04	2.5 (10 min)	302
22	350	5.93	13 (10 min)	361

Table 6. Calculated Spent Nuclear Fuel Oxidation Rate for the Forced Convection Temperatures.

TGA Run #	Test Temperature (°C)	Ballinger Calculated Temperature (°C)	Observed Rate* (mg/cm ² ·min)	Calculated Rate** (mg/cm ² ·min)	Observed Rate/Calculated Rate
18	144	238	0.43	0.012	36
	144	155	0.049	2.2×10^{-4}	223
23	150	150	1.7×10^{-3}	1.6×10^{-4}	11
18b	150	153	0.015	1.9×10^{-4}	79
	150	181	0.15	9.0×10^{-4}	167
	150	191	0.24	1.5×10^{-3}	160
7	300	342	0.14	0.42	0.3
	300	331	0.10	0.31	0.3
	300	321	0.070	0.23	0.3
	300	374	0.24	1.0	0.2
21a	300	320	0.10	0.22	0.5
22	350	455	0.52	6.3	0.08

*Estimated from the weight gain, ΔW , in Table 1 and the initial sample geometrical area.

**Calculated using the dry air oxidation rate equation of Pearce et al. (Pearce 1988) and the calculated temperature of R. G. Ballinger.

A P P E N D I X A

**FURTHER ANALYSIS AND CONCLUSIONS RELATED TO SNFCT97:004
AND OTHER THERMO-GRAVIMETRIC ANALYSIS BASED
ON OXIDATION STUDIES**

HNF-1506, Rev. 0

Spent Nuclear Fuel Technical Assistance Group(TAG)

J. C. DeVine (Head), Polestar Applied Technology
R. G. Ballinger, Massachusetts Institute of Technology
T. L. Bradley, Duke Engineering & Services
D. G. Strawson, MPR Associates
R. H. Steele, MPR Associates
J. D. Trotter, Polestar Applied Technology
R.F. Williams, WTA

Bldg. 2752E-F107
Phone 509-373-7755
FAX (509) 372-2303

MEMO

To: Dr. P. G. Loscoe
From: R. G. Ballinger
CC: J. C. DeVine
Date: 4/16/97
Subject: Further Analysis & Conclusions Related to SNFCT97:004 and Other TGA Based Oxidation Studies

A detailed analysis of the data presented in SNFCT97:004 was presented in an earlier report [1]. One of the conclusions of this analysis was that the data presented in SNFCT97:004 represented a number of processes which were occurring simultaneously during the TGA runs and that analysis of the data must take this into account in deriving any information concerning rates of oxidation. One of the phenomena that was postulated to be occurring was the cracking up of the samples which exposed fresh metal to the environment. Exposure of fresh metal to the environment resulted in regions of the sample which would react at a much higher, parabolic, rate than other regions of the sample which were oxidizing in the linear regime. This process manifested itself as sharp jumps in the weight gain over short intervals of time. Since essentially all (all but one instance) of these jumps were not accompanied by a simultaneous burst of hydrogen the likelihood of these events being due to hydride reaction events was considered very small. The above conclusions are still considered valid. However, the author has further analyzed these jumps in weight gain to evaluate the potential effect of reaction generated heat in aggravating the process during these events. The sample temperature is the critical parameter in establishing the rate of reaction. A 10°C increase in temperature can be expected to result in an approximate factor of two in the reaction rate [2]. Thus, the generation of substantial reaction heat (1080 kJ/moleU for the uranium-oxygen reaction) could result in a "positive feedback" situation in which, if the heat is not adequately removed by the atmosphere, reaction heat increases sample temperature which further increases the reaction rate and so on until very high temperatures are reached. The possibility for this situation occurring was investigated and is reported here.

Two sets of analysis were conducted: (1) an estimate of the adiabatic temperature increase which could occur during rapid weight gain events and (2) a analysis of the effect of forced convection heat transfer to the gas stream on reducing sample surface temperature during a rapid weight gain event.

1.0 Adiabatic Temperature Rise

For this analysis it was assumed that all of the reaction generated heat during a rapid weight gain event went into raising the sample temperature. The specific heat of uranium metal was assumed to be constant at 0.12 J/g-K. A more rigorous analysis would take the variation of specific heat with temperature into account. However, as will be shown in the discussion, this assumption was adequate for this analysis.

2.0 Forced Convection Heat Transfer

HNF-1506, Rev. 0

The forced convection analysis was conducted by modeling the system as heat transfer from a sphere suspended in a gas stream flowing in a pipe. Since the author was not able to get the physical dimensions of the TGA apparatus and since the analysis was only considered preliminary it was assumed that the pipe diameter was 2.54 cm. However, the assumption of spherical geometry will result in an upper bound on the heat transfer coefficient for the system. Thus, for the purposes of the preliminary analysis one can assume that the actual sample surface temperature during a rapid oxidation event will lie between the adiabatic temperature and the forced convection wall temperature but much closer to the forced convection temperature. One additional consideration-the transient nature of the process must be considered in further analysis. As will be shown below, the time interval over which the event occurs is a critical parameter. In the extreme case where the event takes place instantaneously the actual surface temperature may be much closer to the adiabatic temperature.

The convective heat transfer correlation used for this analysis was that of Whitaker [3].

Where Re is the Reynolds number based on the sphere diameter, Pr is the Prandtl Number, and μ is the viscosity of the gas evaluated at the free stream temperature and the sample surface temperature respectively.

$$Nu = 2 + \left(0.4 Re^{0.5} + 0.06 Re^{2/3} \right) Pr^{0.4} \left(\frac{\mu_{stream}}{\mu_{wall}} \right)^{0.25}$$

For this analysis it was assumed that the free stream and wall viscosity were equal. Based on the results of the analysis this assumption would result in an error of approximately 20% in the heat transfer coefficient in the extreme case. This would result in an error of approximately 10°C in temperature.

Additional assumptions were that the gas properties were constant, independent of temperature as were the properties of uranium metal.

The analysis was programed using Mathcad. The Mathcad program is included as Appendix 1.

3.0 Results and Discussion

The results of this analysis are shown in Table 1. The analysis was done using weight gain jumps in the TGA runs used to generate the data in SNFCT97-004. The effect of forced convection is very significant. However, for cases where the weight gain jump occurred over a short time period (<approximately 10min) it is likely that the sample temperature was so much higher than the gas temperature as to make any interpretation of the data for oxidation in this region meaningless. In fact, it is likely that a possible explanation for the weight loss after these events is that the sample surface temperature ramped up high enough and fast enough to literally cause something akin to ablation of the surface. Once the surface layer was "blown off" the high temperature material was removed and the sample was then free to oxidize at the free stream temperature. The ratio of specific heat to conductivity for uranium metal is approximately 0.5. Thus for very fast transients one would expect that the sample temperature would not be uniform.

The effect of rapid heat introduction as a result of exposure of fresh metal coupled with inadequate heat removal has very likely resulted in the positive feedback phenomena suggested earlier. Thus it is very unlikely that the actual sample temperature was known within 20°C or even more for fast transients. Since many of these transients were used as the basis for data included in the PNNL rate law it is questionable whether the data and associated rate law are of any validity.

4.0 Conclusions

Based on this analysis the following conclusions are suggested:

HNF-1506, Rev. 0

It is likely that the use of ANY rapid weight gain events (events occurring over a period of time of the order of 10-20 minutes) for the determination of rate law information should be approached with GREAT caution.

The value of ANY of the data generated as part of the TGA based oxidation studies will have a VERY high degree of uncertainty and, as such, can be expected to provide little information concerning the behavior of N-Reactor fuel.

Any oxidation and/or drying tests that are to be performed in the future should take due consideration of the heat transfer conditions as they effect actual sample temperatures during tests.

Table 1

Summary of Heating Analysis

Sample ID#	Gas Temp.,C	Sample Wt,g	ΔW ,mg	T(Adiabatic)	T_{wall} (Conv.)
10-S3-F2(TGA18)	144	5.41	6.5 (6 min)	338	238
	144	5.41	2.5 (20 min)	273	155
5-S1A-E2-R1A(TGA23)	150	3.32	0.15 (70 min)	162	150
10-S1-C4(TGA18b)	150	6.35	0.2 (5 min)	160	153
	150	6.35	0.4 (1 min)	187	181
	150	6.35	3.1 (5 min)	287	191
5-S1A-A2C(TGA7)	300	6.88	8 (20 min)	627	342
	300	6.88	3 (10 min)	422	331
	300	6.88	5 (25 min)	504	321
	300	6.88	7 (10 min)	586	374
10-S1-C3(TGA21a)	300	6.04	2.5 (10 min)	416	320
10-S1-C2(TGA22)	350	5.93	13 (10 min)	966	455

5.0 References

1. Ballinger, R. G., "An Evaluation of Oxidation Data for N-Reactor Spent Nuclear Fuel in Dry and Moist Air", Report prepared for P. G. Loscoe, 4/6/97.
2. Pearce, R. J., "A Review of the Rates of reaction of Unirradiated Uranium in Gaseous Atmospheres", CEBG Report RD/B/6231/R89, October, 1989.
3. Whitaker, S., "Forced Convection Heat Transfer Correlations for Flow in Pipes Past Flat Plates, Single Cylinders, Single Spheres, and Flow in Packed Beds and Tube Bundles", AIChE J., Vol. 18, 1972, pp. 361-371.

A P P E N D I X B

**CALCULATIONAL SHEETS FOR THERMAL ANALYSIS OF THERMO-
GRAVIMETRIC ANALYSIS OF SAMPLE TEMPERATURES**

Westinghouse
Hanford Company

TASK RECORD

Page

1

Task Spec No. _____

Cog Eng ER Crumer

Title _____

Date July 21, 1997

Task Record No. _____

Reviewer Blair, CDate 9/10/97

Calculation of SNF sample temperatures
for Adiabatic temperature rise.

Assume all reaction generated heat goes
into raising the sample temperature.

$$T = T_i + \frac{\dot{q}}{m c_p}$$

$$\dot{q} = (\Delta W)(33.75 \frac{J}{mg})$$

where T_i = initial temperature, °C

$\dot{q}$ = heat input, joules

m = sample mass, mg

c_p = sample specific heat, $0.12 \frac{J}{gK}$

ΔW = sample weight gain, mg

$$T = T_i + \frac{\Delta W (33.75)}{m (.12)}$$

Results from this equation are given
in Table 1.

Westinghouse
Hanford Company

TASK RECORD

Page

2

Task Spec No. _____

Cog Eng ER Cramer

Title _____

Date July 21, 1997

Task Record No. _____

Reviewer BlairDate 9/10/97

Calculate temperature of SNF sample assuming forced convection heat transfer.

Use equation for heat transfer from a sphere suspended in a gas stream flowing in a 1" diameter pipe.

$$Nu = 2 + \left[.4(Re)^{.5} + .06 Re^{.2/3} \right] Pr^{.4} \left(\frac{\mu_{stream}}{\mu_{wall}} \right)$$

where Re is the Reynolds number based on the sphere diameter, Pr = Prandtl No. and μ = viscosity.

$$\text{Assume } \mu_{stream} = \mu_{wall}$$

$$Re = \frac{\rho v d}{\mu} = \frac{(.0384 \frac{lb}{ft^3}) (.027 \frac{ft}{s}) (.029 ft)}{1.95 \times 10^{-5} \frac{lb}{ft \cdot s}} = 1.54$$

$$Nu = 2 + \left[.4(1.54)^{.5} + .06(1.54)^{.2/3} \right] (.68)^{.4} = 2.49$$

calculate heat transfer coefficient, h

$$h = \frac{Nu(k)}{d} = 2.49 \left(\frac{.024 \frac{Btu}{hr \cdot ft \cdot F}}{.029 ft} \right) = 2.06 \frac{Btu}{hr \cdot ft^2 \cdot F}$$

Westinghouse
Hanford Company

TASK RECORD

Page
3

Task Spec No. _____

Title _____

Task Record No. _____

Cog Eng ER CramerDate July 21, 1997Reviewer Blain D.Date 9/10/98

$$h = 2.06 \frac{B + u}{k r - r^2 - F} \left(\frac{5.274 \times 10^{-4} \frac{W}{cm^2 \cdot K}}{B / k r - r^2 - F} \right) = 1.17 \times 10^{-3} \frac{W}{cm^2 \cdot K}$$

$$\text{Sphere volume} = \frac{6.88 \text{ gm}}{19 \text{ gm/cm}^3} = .362 \text{ cm}^3$$

$$.362 = \frac{4}{3} \pi r^3$$

$$r = .442$$

$$\text{Sphere surface area} = 4 \pi r^2 = 2.457 \text{ cm}^2$$

$$\text{Reaction Heat } \dot{q} = \frac{\Delta W}{t} \left(33.75 \frac{J}{g} \right)$$

where ΔW = sample weight gain, g
 t = time, sec

$$\frac{\Delta W (33.75)}{t} = h A \Delta T$$

$$\frac{\Delta W (33.75)}{t} = \left(1.17 \times 10^{-3} \frac{W}{cm^2 \cdot K} \right) (2.457 \text{ cm}^2) \Delta T$$

Solve this equation for ΔT . Results are given in Table 2.

Westinghouse
Hanford Company

TASK RECORD

Page

4

Task Spec No. _____

Cog Eng E.R. Crumer

Title _____

Date July 23, 1997

Task Record No. _____

Reviewer J. BlairDate 9/11/97

Calculate SNF temperature assuming convection and radiation from top surface and conduction from bottom surface through an air gap.

$$\dot{q} = \dot{q}_{\text{conv}} + \dot{q}_{\text{rad}} + \dot{q}_{\text{cond}} \quad \text{--- Equation A}$$

$\dot{q}$ = reaction heat

$\dot{q}_{\text{conv}}$ = convection heat from top surface

$\dot{q}_{\text{rad}}$ = radiation heat from top surface

$\dot{q}_{\text{cond}}$ = conduction heat from bottom surface

$$\dot{q} = \frac{\Delta W}{t} \left(3.395 \times 10^7 \frac{\text{J}}{\text{kg}} \right) \quad \text{--- reaction heat}$$

Westinghouse
Hanford Company

TASK RECORD

Page
5

Task Spec No. _____

Cog Eng

ER, Crumet

Title _____

Date

July 23, 1997

Task Record No. _____

Reviewer

Blair De

Date

7/11/97

$$\dot{q}_{conv} = h A \Delta T$$

$$\text{Estimate } h = 2 \frac{Btu}{hr \cdot ft^2 \cdot F} = 1.135 \times 10^{-3} \frac{W}{cm^2 \cdot K}$$

$$A = (.365 \text{ in}) (.362 \text{ in}) = .1394 \text{ in}^2 = 0.899 \text{ cm}^2$$

$$\dot{q}_{conv} = (1.135 \times 10^{-3}) (.899) \Delta T = (10.2 \times 10^{-4}) \Delta T$$

Westinghouse
Hanford Company

TASK RECORD

Page

6

Task Spec No. _____

Title _____

Task Record No. _____

Cog Eng ER CramerDate July 23, 1997Reviewer ESain QDate 9/11/97

$$\dot{q}_{\text{rad}} = A F \sigma (T_s^4 - T_F^4)$$

Assume view factor between furnace and SNF sample is 1.0. Gray-body shape factor, F , is then:

$$F = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

graphite furnace wall emissivity $\epsilon_1 = 0.98$

SNF sample emissivity $\epsilon_2 = 0.7$

$$F = \frac{1}{\frac{1}{.98} + \frac{1}{.7} - 1} = .69$$

Stephan-Boltzman constant $\sigma = 5.6699 \times 10^{-12} \frac{\text{W}}{\text{cm}^2 \cdot \text{K}^4}$

$$A = .899 \text{ cm}^2$$

$$\dot{q}_{\text{rad}} = .899 (.69) 5.6699 \times 10^{-12} (T_{\text{SNF}}^4 - T_F^4) \frac{\Delta T}{\Delta T}$$

$$\dot{q}_{\text{rad}} = \left[\frac{3.517 \times 10^{-12} (T_{\text{SNF}}^4 - T_F^4)}{\Delta T} \right] \Delta T$$

where T_s is SNF sample temperature and
 T_F is furnace temperature

Westinghouse
Hanford Company

TASK RECORD

Page
7

Task Spec No. _____

Cog Eng ER Cramer

Title _____

Date July 25, 1997

Task Record No. _____

Reviewer Blair G.Date 9/11/97

Air thermal conductivity, $K = 4.15 \times 10^{-4} \frac{W}{cm \cdot K}$
 Assume length of heat transfer path $= \frac{1}{2} \text{ mm} = .05 \text{ cm}$

Neglect resistance of quartz crucible

$$\dot{q}_{\text{cond}} = \frac{KA}{l} \Delta T$$

$$\dot{q}_{\text{cond}} = \frac{(4.15 \times 10^{-4}) \cdot .899}{.05} \Delta T$$

$$\dot{q}_{\text{cond}} = (74.6 \times 10^{-4}) \Delta T$$

Substitute everything into Equation A

$$\frac{\Delta W}{t} (3395 \times 10^3) = \left[\overset{\text{heat of reaction}}{10.2 \times 10^{-4}} + \overset{\text{convection term}}{3.517 \times 10^{-12} (T_{\text{sup}}^4 - T_F^4)} + \overset{\text{radiation term}}{74.6 \times 10^{-4}} \right] \Delta T$$

Temperature results calculated by this equation are given in Table 3.

Sample weight gain, ΔW , and time, t are also shown in Table 3.

Westinghouse
Hanford Company

TASK RECORD

Page
8

Task Spec No. _____ Cog Eng ER Cramer
 Title _____ Date July 25, 1997
 Task Record No. _____ Reviewer Blair G.
 Date 9/11/97

Now consider the heat loss through the contact area between the SNF sample and the quartz crucible.

Assume 1% of SNF area is in contact with quartz crucible

Heat transfer area thru quartz:

$$A = .01 (.899 \text{ cm}^2) = .00899 \text{ cm}^2$$

$$\text{length through quartz} = (.015 \text{ in}) 2.54 = .0381 \text{ cm}$$

quartz thermal conductivity:

$$\parallel \text{ to crystal axis, } K = .0527 \frac{\text{W}}{\text{cm-K}}$$

$$\perp \text{ to crystal axis, } K = .0353 \frac{\text{W}}{\text{cm-K}} \leftarrow \text{use this one to be conservative}$$

$$\text{quartz conductance } U_q = \frac{KA}{d} = \frac{(.0353)(.00899)}{.0381}$$

$$U_q = .00833 \frac{\text{W}}{\text{K}}$$

Westinghouse
Hanford Company

TASK RECORD

Page

9

Task Spec No. _____

Cog Eng ER Crainer

Title _____

Date July 25, 1997

Task Record No. _____

Reviewer Blair BeDate 9/16/97

length through SNF maximum = .25 in = .635 cm

Use heat transfer area mid-way between
contact area and top of SNF

$$A = .133 \text{ cm}^2$$

$$\text{SNF conductance, } U_{\text{SNF}} = \frac{kA}{L}$$

$$U_{\text{SNF}} = \frac{\left(.30 \frac{\text{W}}{\text{cm}^2 \cdot \text{K}} \right) (.133 \text{ cm}^2)}{.635 \text{ cm}} = .0628 \frac{\text{W}}{\text{K}}$$

Westinghouse
Hanford Company

TASK RECORD

Page

10

Task Spec No. _____

Cog Eng

ER Cramer

Title _____

Date

July 25, 1997

Task Record No. _____

Reviewer

Blair G.

Date

9/11/97

Alumina Pedestal Conductance

$$d = .165 \text{ in} = .419 \text{ cm} \quad (\text{guess is same as pedestal dia.})$$

Use heat transfer area mid-way between
quartz contact area and other side
of alumina head

$$A = .066 \text{ cm}^2$$

$$\text{Alumina } U = \frac{KA}{L} = \frac{(.17 \frac{\text{W}}{\text{cm} \cdot \text{K}})(.066 \text{ cm}^2)}{.419 \text{ cm}} = .0268 \frac{\text{W}}{\text{K}}$$

Calculate overall conductance, U

$$U = \frac{1}{\frac{1}{.00933} + \frac{1}{.0628} + \frac{1}{.0268}}$$

$\uparrow$ quartz
crucible $\uparrow$ uranium
SNF $\uparrow$ alumina
pedestal

$$U = .00577 \frac{\text{W}}{\text{K}} \quad \text{--- For 1\% contact area}$$

$$U = .0577 \frac{\text{W}}{\text{K}} \quad \text{--- For 10\% contact area}$$

Westinghouse
Hanford Company

TASK RECORD

Page

11

Task Spec No. _____

Cog Eng

ER Cramer

Title _____

Date

July 25, 1997

Task Record No. _____

Reviewer

B. G.

Date

9/11/97

For analysis of 1% or 10% contact area, add the above conductance term to equation A:

$$\dot{q} = \dot{q}_{\text{conv}} + \dot{q}_{\text{rad}} + \dot{q}_{\text{cond}} + \dot{q}_{\text{contact}}$$

$$\frac{\Delta W (3.395 \times 10^7)}{t} =$$

$$\left[10.2 \times 10^{-4} + \frac{3.517 \times 10^{-12} (T_{\text{SNF}}^4 - T_F^4)}{\Delta T} + 74.6 \times 10^{-4} + u \right] \Delta T$$

Temperature results calculated by this equation are given in Table 4 for 1% contact area, and Table 5 for 10% contact area.

Westinghouse
Hanford Company

TASK RECORD

Page
12

Task Spec No. _____

Cog Eng ER Crumer

Title _____

Date Aug 25, 1997

Task Record No. _____

Reviewer Blair ClineDate 9/10/97

Calculate Time Constant for
thermocouple response to step change
in surface temperature of SNF sample.

Assume lumped heat capacity system.

$$\text{Time constant } \tau = \frac{PVc_p}{hA}$$

ρ = uranium density

V = uranium volume

c_p = uranium heat capacity

h = heat transfer coefficient from
uranium surface to thermocouple

A = heat transfer area

Sample thickness = 0.25 inch

$$V = \frac{(0.25 \text{ in}) A}{12 \text{ in/ft}} = .02083 A$$

$$\rho = 1167 \text{ lb/ft}^3$$

$$c_p = .031 \frac{\text{Btu}}{\text{lb-F}}$$

Westinghouse
Hanford Company

TASK RECORD

Page
13

Task Spec No. _____

Cog Eng ER Cramet

Title _____

Date Aug 25, 1997

Task Record No. _____

Reviewer Blair, CDate 9/10/97Define overall h as :

$$h = \frac{1}{\frac{l_u}{K_u} + \frac{l_2}{K_2} + \left[\frac{1}{\frac{l_{air}}{K_{air}} + \sigma F \frac{T_s^4 - T_a^4}{T_s - T_a}} \right]^{-1}}$$

↑ Radiation Term

 l = length K = conductivity

$$l_u = \frac{.25}{3.12} = .00694 \text{ Ft} \quad - \text{assume } \frac{1}{3} \text{ of actual thickness}$$

$$K_u = 16.7 \frac{\text{Btu}}{\text{hr-ft-F}}$$

 $l_{air} = 0$ For good contact case

$$= .5 \text{ mm} = .00164 \text{ Ft} \text{ For poor thermal contact}$$

$$K_{air} = .022 \frac{\text{Btu}}{\text{hr-ft-F}}$$

$$l_2 = .02 \text{ in} = .0017 \text{ Ft} \quad - \text{thickness of quartz crucible}$$

$$K_2 = 2.89 \frac{\text{Btu}}{\text{hr-ft-F}}$$

Westinghouse
Hanford Company

TASK RECORD

Page
14

Task Spec No. _____

Cog Eng ER Cramer

Title _____

Date Aug 25, 1997

Task Record No. _____

Reviewer [Signature]Date 9/18/97

$$\sigma = .1714 \times 10^{-8} \frac{Btu}{hr \cdot ft^2 \cdot F^4} \quad - \text{Stephan Boltzmann}$$

$$F = \frac{1}{\frac{1}{\epsilon_q} + \frac{1}{\epsilon_u}} - 1 = \frac{1}{.5 + \frac{1}{.7} - 1} = .41$$

where ϵ_q = quartz emissivity ϵ_u = uranium emissivity

For the radiation term, assume

$$T_s = 575^\circ F = 1035^\circ R$$

$$T_q = 572^\circ F = 1032^\circ R \quad (300^\circ C)$$

For good thermal contact, the surfaces are in contact so there is no radiation term and no air term.

Westinghouse
Hanford Company

TASK RECORD

Page

15

Task Spec No. _____

Cog Eng

ER Cramer

Title _____

Date

Aug 25, 1987

Task Record No. _____

Reviewer

J. L. L. L.

Date

9/18/87

For good thermal contact case:

$$h = \frac{1}{\frac{.00694}{16.7} + \frac{.00167}{2.89}} = 1007 \frac{Btu}{hr-ft^2-F}$$

$$\tau = \frac{(1167 \frac{lb}{ft^3})(.02083 ft) A (.031 \frac{Btu}{lb-F}) (3600 \frac{s}{hr})}{(1007 \frac{Btu}{hr-ft^2-F}) A}$$

$$\tau = 2.7 \text{ seconds}$$

Westinghouse
Hanford Company

TASK RECORD

Page

16

Task Spec No. _____

Cog Eng ER Cramer

Title _____

Date Aug 25, 1997

Task Record No. _____

Reviewer John DoeDate 9/10/97

For Poor Thermal contact Case :

$$h = \frac{1}{\frac{.00694}{16.7} + \frac{.00167}{2.89} + \left[\frac{1}{\frac{.022}{.00164} + .1714 \times 10^{-8} (.41) \frac{1035^4 - 1032^4}{1035 - 1032}} \right]}$$

$$h = \frac{1}{4156 \times 10^{-7} + 5779 \times 10^{-7} + \frac{1}{.1341 + 3.103}}$$

$$h = 16.25 \frac{B + u}{hr - ft^2 - F}$$

$$\tau = \frac{(1167 \text{ } 1b/ft^3) (.02083 \text{ ft}) A (.031 \frac{B + u}{1b - F}) (3600 \frac{s}{h})}{16.25 \frac{B + u}{hr - ft^2 - F}}$$

$$\tau = 167 \text{ seconds}$$

DISTRIBUTION SHEET

To Distribution	From SNF Characterization Project/ 2T720	Page 1 of 1 Date October 3, 1997
Project Title/Work Order Thermal Analysis of Thermo-Gravimetric Measurements of Spent Nuclear Fuel Oxidation Rates		EDT No. 620796 ECN No.

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
------	------	-----------------------------	-----------	------------------------------	-----------------

Fluor Daniel Hanford, Inc.

E. W. Gerber	R3-11	X
<u>Duke Engineering & Services Hanford, Inc.</u>		
R. B. Baker	H0-40	X
J. R. Frederickson	R3-86	X
F. G. Hudson	R3-11	X
L. A. Lawrence (5)	H0-40	X
B. J. Makenas	H0-40	X
R. P. Omberg	H0-40	X
D. W. Smith	R3-15	X
J. A. Swenson	R3-11	X
D. J. Trimble	H0-40	X
SNF Project Files	R3-11	X
Central Files	A3-88-31-07	X

Lockheed Martin Hanford Corp.

J. J. Irwin	H0-34	X
<u>Numatec Hanford Corporation</u>		
E. R. Cramer	H0-34	X
T. A. Flament	K9-46	X
C. R. Miska	R3-86	X
J. P. Sloughter	H5-49	X

Pacific Northwest National Laboratory

J. Abrefah (2)	P7-27	X
S. C. Marschman	P7-27	X

U.S. Department of Energy,
Richland Operations Office

P. G. Loscoe	S7-41	X
E. D. Sellers	S7-41	X
J. Shuen	S7-41	X