THE BECKMAN 7C THERMAL CELL (HYDROGEN MONITOR) EXPERIMENTS

M. L. Carboneau

D. A. Petti

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1. Introduction

Small scale laboratory experiments were conducted at the IRC (INEL Research Center) on a Beckman model 7C thermal conductivity cell under various sample input conditions. The purpose of the experiments was to provide a better understanding of the response of the hydrogen monitor during the Power Burst Facility (PBF) Severe Fuel Damage (SFD) tests. The main objective of the experiments was to identify conditions others than increased hydrogen concentration that would produce a positive output signal similar to that observed late in the PBF SFD 1-4 test. Such a signal occurred during the argon gas cooling of the bundle, a time period when little or no hydrogen was expected. To meet the test objective, the effects of flowrate, gas composition, temperature, water aerosol, steam, and the humidity content of the input sample were studied. Both steady state and transient type experiments were performed to understand the monitor response under varied conditions. The results of these experiments are summarized in this report.

Section 2 presents the general experiment design and equipment layout. The functional characteristics of the Wheatstone bridge are also identified. Section 3 discusses the steady state 'dry' (without the addition of water to the input gas stream) experiments and reports the results of the monitor output voltage as a function of gas composition, and flow rate. The steady state 'wet' (with water moisture) test results are presented in Section 4, and the water aerosol test results are reported in Section 5. The transient experiment results are summarized in Section 6 and the main conclusions of the report are listed in Section 7. Finally, the impact of these experiments on the interpretation of the SFD test data is discussed in Section 8.

2. Experiment Design

A functional diagram of the Wheatstone bridge used in the thermal conductivity analyzer is shown in Figure 1. During all experiments, the bridge power supply, as recommended by engineers at Beckman Industrial, was set at 67.9 mA (as measured at room temperature). This current

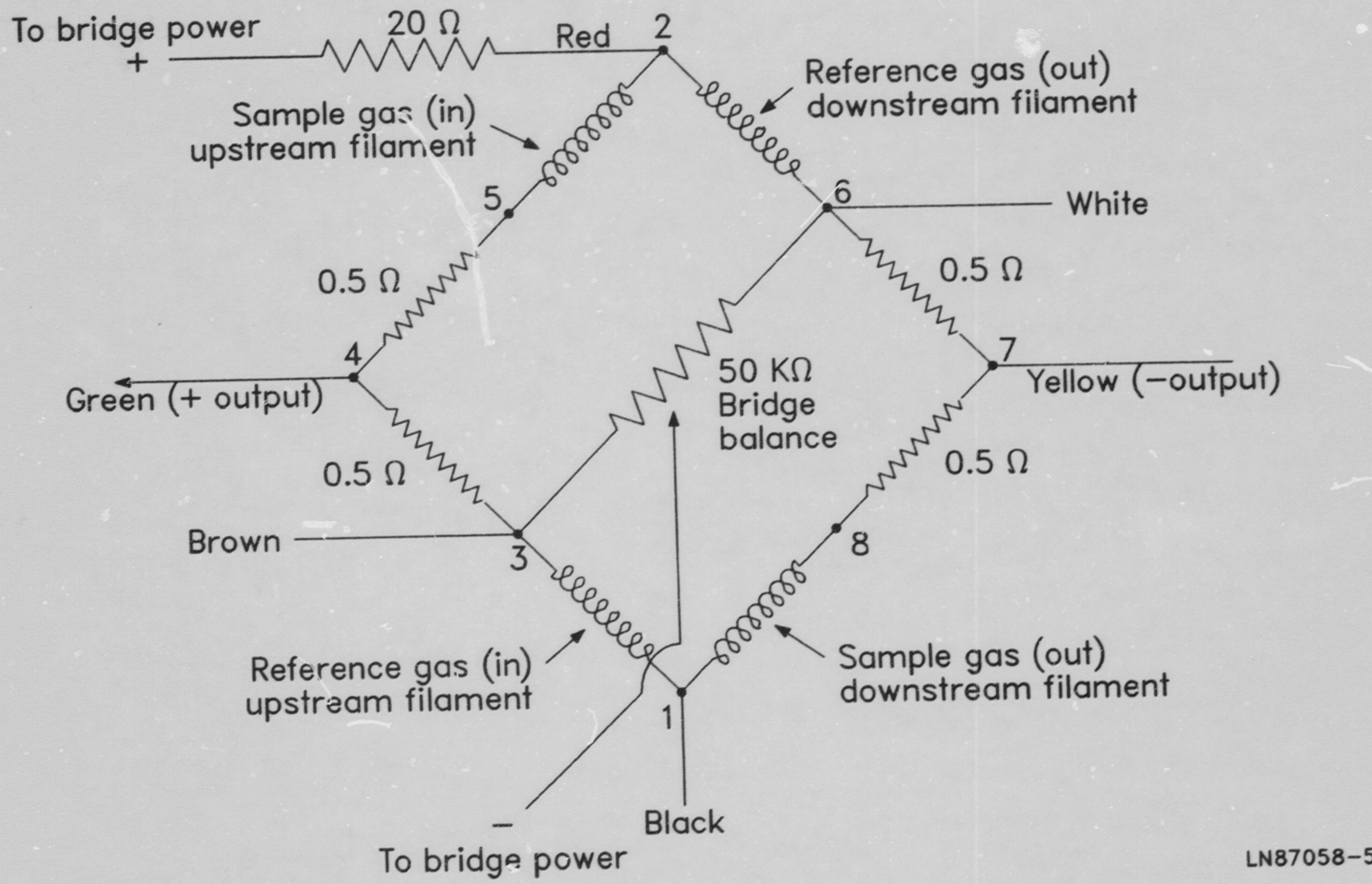

Figure 1. Functional diagram of the Wheatstone bridge circuit as configured in the Beckman 7C thermal cell.

resulted in a voltage drop of 1.34 V across the bridge and 2.8 V at the power supply. This voltage drop is lower than the 5 V mentioned in the manufacturer's manual; however, conversations with applications engineers at Beckman Industrial indicate that the critical factor is bridge current, and that for all cases the recommended bridge current should be less than 70 mA.

3. Steady State Experiments Without Water

The first set of experiments that were conducted were steady state 'dry' experiments. These experiments tested the response of the thermal cell to different input gas compositions, flow rates, and gas temperature. These initial experiments did not include water vapor or water aerosols in the carrier gas. The general equipment layout used during the first series of steady state experiments is illustrated in Figure 2. In all of the experiments, helium was used instead of hydrogen for safety reasons. The thermal conductivity of helium is very similar to that of hydrogen. The range of flow rates that were selected in these experiments span the possible flow conditions that could have occurred during the SFD tests. The Wheatstone bridge output voltage of the thermal cell is recorded in Tables 1 through 5 for various mixtures and flow rates of He, N_2, and Ar under dry gas conditions. The effect of oven temperature on the monitor response was evaluated during this series of tests and the results are also shown in Table 5.

Selected data from Tables 1, 2 and 3 are plotted in Figures 3 and 4. Based on the information shown in Table 1 and Figure 3, the 7C thermal conductivity cell produces about the same output signal independent of the volumetric flow rates of He and N_2 up to 500 sccm as long as the He to N_2 ratio and gas temperature are constant and the sample is dry. This implies that for He and N_2 gas mixtures the 7C cell output voltage is not dependent on the total gas flow rate as long as the total flow rate is less than 500 sccm. Consequently, the performance of the thermal cell exceeds the manufacturer's recommended maximum flow rate condition of 350 sccm and the nominal design flow rate of 250 sccm used during the SFD experiments.

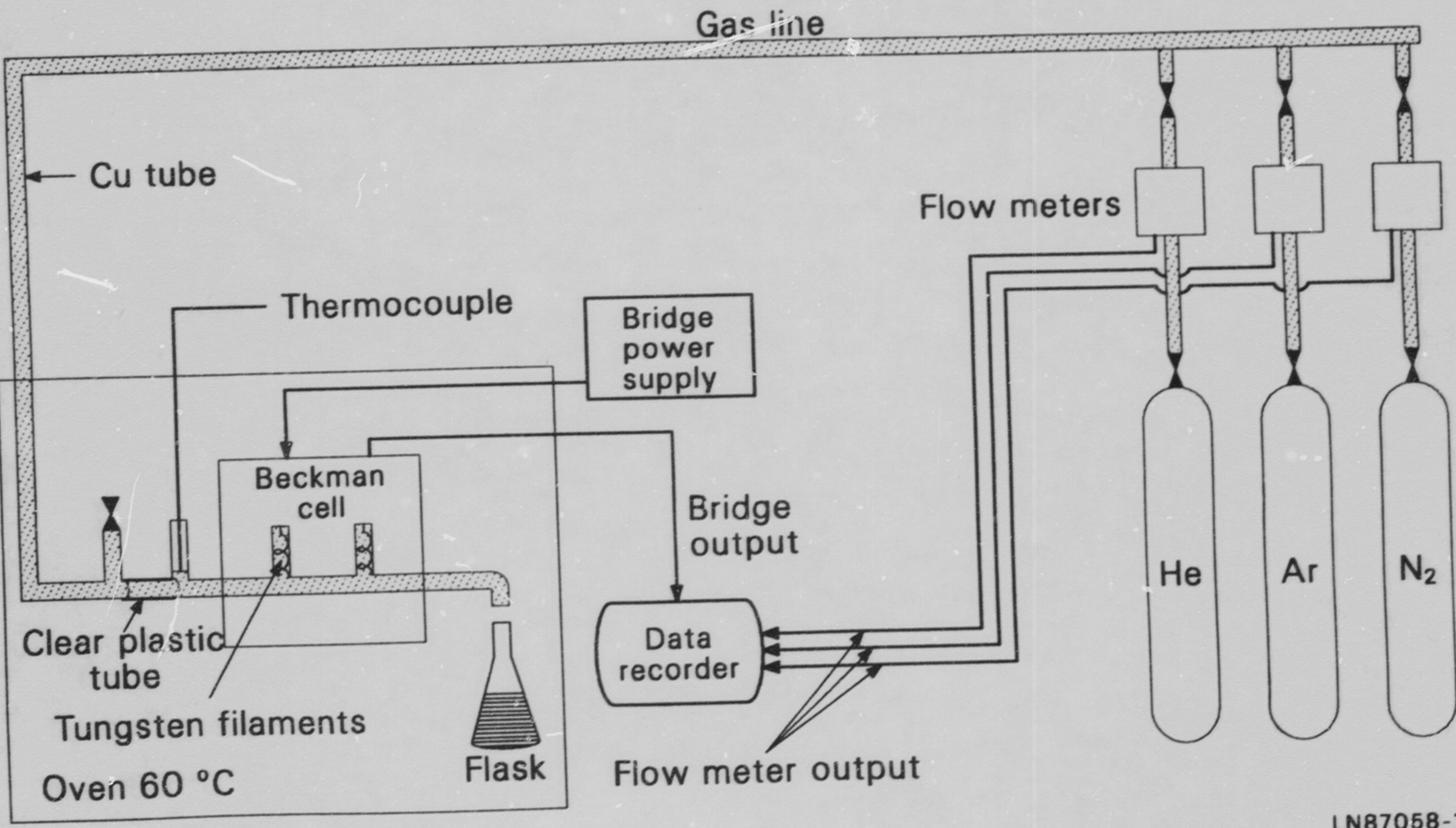

Figure 2. Diagram of equipment layout used for the first series of steady state experiments to test the 7C cell under various dry gas conditions.

TABLE 1. EXPERIMENT 1 STEADY STATE TEST RESULTS: EFFECT OF He/N_2 GAS MIXTURES AND FLOW RATE ON MONITOR (BRIDGE) VOLTAGE[a].

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Comments and notes[b]	Bridge Output (mV)
263.0	0.0	0.0	Span gas check	45.7
0.0	270.0	0.0	zero gas check	0.0
79.6	314.0	0.0	20% He	16.8
39.4	163.5	0.0	19% He	17.2
19.0	81.0	0.0	19% He	17.9
101.4	409.0	0.0	20% He	16.6
50.0	197.0	0.0	20% He	17.6
51.4	52.0	0.0	50% He	32.0
97.2	95.5	0.0	50% He	32.0
200.0	203.3	0.0	50% He	31.4
247.0	252.0	0.0	50% He	31.3
123.0	128.0	0.0	49% He	31.4
79.6	19.8	0.0	80% He	41.0
159.8	36.6	0.0	81% He	41.2
316.0	74.4	0.0	81% He	41.1
399.0	98.1	0.0	80% He	40.9
197.0	51.6	0.0	79% He	40.8

* sccm = standard cubic centimeters per minute.

a. Oven temperature ranged from 120° to 130°F, input gases were not heated above oven temperature, and no water was injected into the thermal cell.

b. Volume percent helium; the balance percentage is nitrogen.

TABLE 2. EXPERIMENT 2 STEADY STATE TEST RESULTS: EFFECT OF N_2/Ar GAS MIXTURES AND FLOW RATES ON MONITOR (BRIDGE) VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Comments and notes[b]	Bridge Output (mV)
0.0	0.0	100.0		-24.6
0.0	0.0	237.0		-25.4
0.0	0.0	505.0		-25.4
0.0	0.0	>1035.0	-c-	-25.2
0.0	100.0	145.0	41% Ar	-14.7
0.0	252.0	245.0	49% Ar	-12.0
0.0	254.0	100.0	28% Ar	-7.1
0.0	197.0	48.6	20% Ar	-5.1

* sccm = standard cubic centimeters per minute.

a. Oven temperature ranged from 120^{o} to 130^{o}F, input gases were not heated above oven temperature, and no water was injected into the thermal cell.

b. The percentage He or Ar shown in the last column is based on volume and not mass, with the balance percentage due to N_2.

c. The Ar flow meter registered a reading above its calibrated range.

TABLE 3. EXPERIMENT 3 STEADY STATE TEST RESULTS: EFFECT OF He/N_2/Ar GAS MIXTURES AND FLOW RATES ON MONITOR (BRIDGE) VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Comments and notes[b]	Bridge Output (mV)
222.0	0.0	0.0	span gas check	45.9
0.0	250.0	0.0	zero gas check	0.0
198.0	0.0	50.7	74% He, 26% Ar	40.2
125.0	0.0	125.0	50% He, 50% Ar	28.3
48.6	0.0	197.0	20% He, 80% Ar	5.5
50.0	0.0	505.0	10% He, 90% Ar	-8.5
48.0	0.0	1003.0	4% He, 96% Ar	-17.3
506.0	0.0	1003.0	34% He, 66% Ar	13.4
506.0	0.0	513.0	50% He, 50% Ar	27.7
260.0	0.0	519.0	33% He, 67% Ar	17.6
50.7	150.0	50.7	20% He, 20% Ar	14.2
51.4	91.6	105.0	21% He, 42% Ar	11.4
51.4	46.5	153.0	20% He, 61% Ar	8.7
47.9	44.9	496.0	8% He, 84% Ar	-8.2
47.9	46.4	980.0	4% He, 91% Ar	-16.3
48.6	492.0	980.0	3% He, 64% Ar	-12.1
47.9	480.0	105.0	8% He, 17% Ar	4.3

* sccm = standard cubic centimeters per minute (e.g. at STP).

a. Oven temperature measured 145°F, input gases were not heated above oven temperature, and no water was injected into the thermal cell.

b. Volume percent helium and argon; balance percentage is nitrogen.

TABLE 4. EXPERIMENT 4 STEADY STATE TEST RESULTS: EFFECT OF INPUT GAS TEMPERATURE, GAS COMPOSITION, AND FLOW RATE ON THE RESPONSE OF THE THERMAL CELL OUTPUT VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Gas Temperature (F)	Bridge Output (mV)
47.9	156.0	52.1	256	12.6
51.4	87.9	108.0	261	11.0
51.4	44.6	148.0	262	8.9
51.4	46.6	151.0	263	8.5
47.2	44.2	498.0	263	-8.9
48.6	47.7	982.0	264	-17.5
49.3	49.4	972.0	265	-13.4
47.9	474.6	104.2	266	3.6
50.7	196.0	0.0	271	16.6
122.0	134.0	0.0	285	30.5
196.5	52.6	0.0	295	40.5
197.2	51.9	0.0	300	40.5

* sccm = standard cubic centimeters per minute.

a. Oven temperature measured 145°F, and input gases were heated to >260°F. Water was not injected into the gas stream for these tests.

TABLE 5. EXPERIMENT 5 STEADY STATE TEST RESULTS: EFFECT OF OVEN TEMPERATURE ON THE RESPONSE OF THE THERMAL CELL OUTPUT VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Oven Temperature (F)	Bridge Output (mV)
196.5	51.9	0.0	176	42.1
196.5	52.0	0.0	121	43.7
197.2	52.1	0.0	101	44.8
197.2	51.5	0.0	70	47.2

* sccm = standard cubic centimeters per minute.

a. Oven temperature measured at less than 176^{o}F with input gases allowed to reach oven temperature but were not heated above this temperature. Water was not injected for these tests.

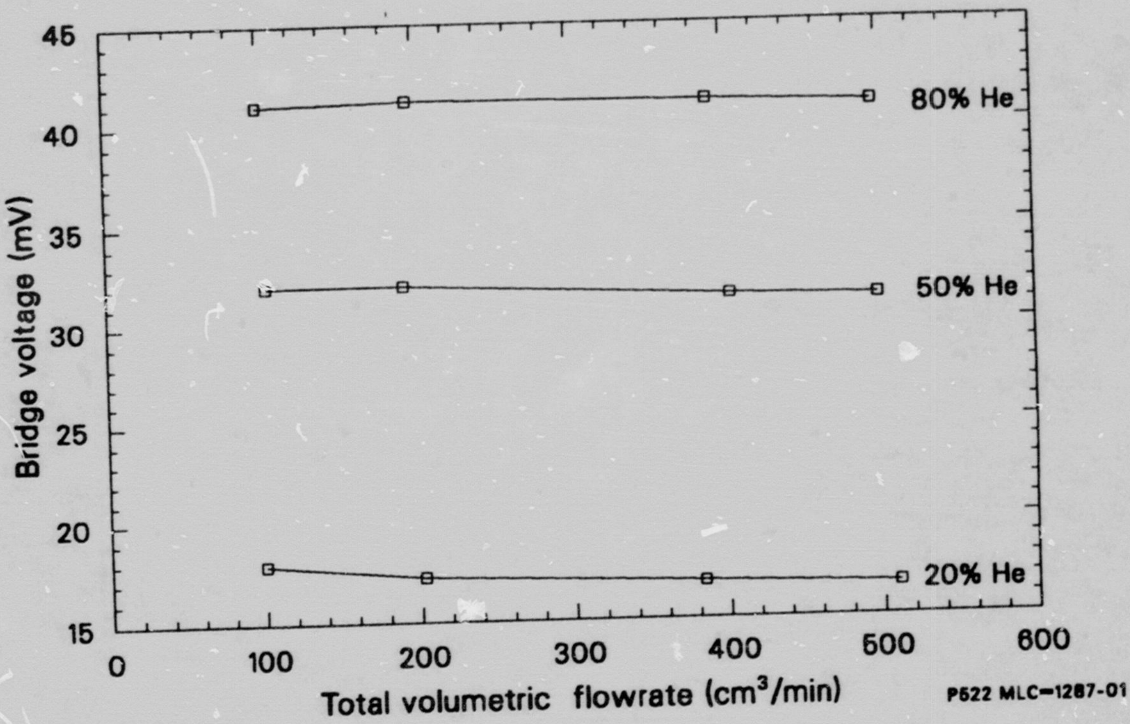

Figure 3. The effect of volumetric flowrate and He/N_2 concentration on the bridge monitor output voltage.

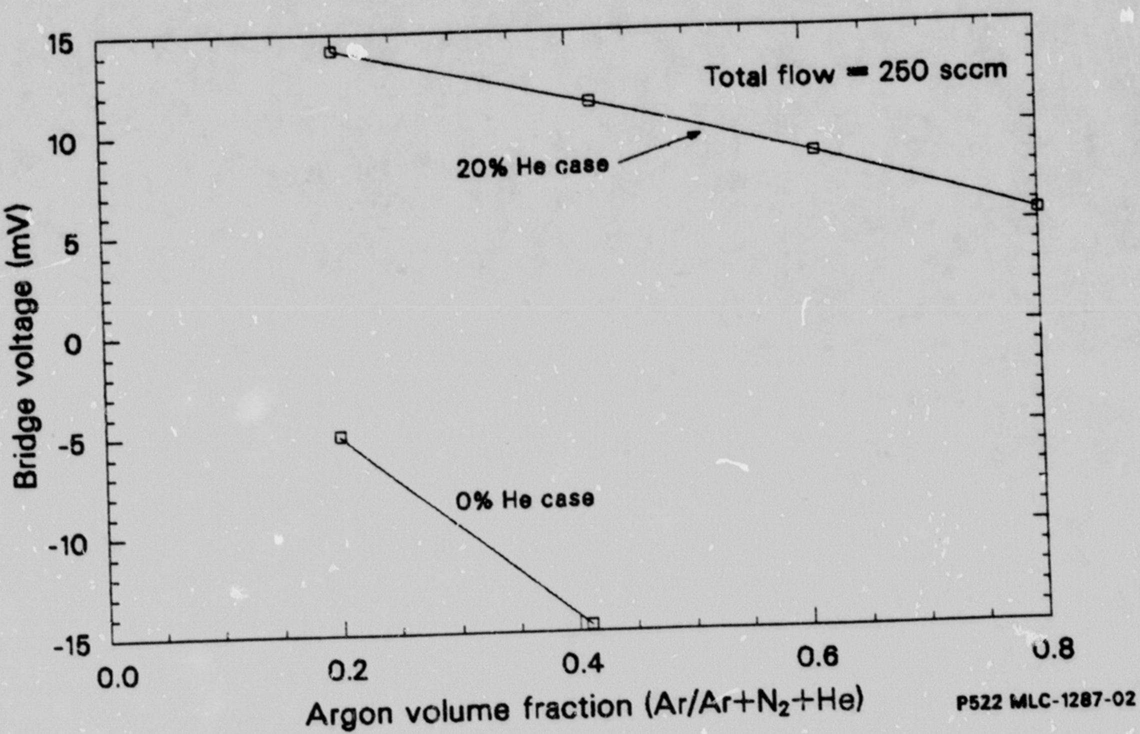

Figure 4. The effect of argon gas on the bridge monitor output voltage at a constant total gas flow rate of 250 sccm.

Based on the data shown in Tables 2 and 3, or Figure 4, Ar gas tends to reduce the cell's output signal. The greater the percentage of Ar that is introduced into the cell, the smaller the output signal. In fact, for high concentrations of Ar with He, or with small concentrations of Ar with no He, the bridge output is negative. Because the thermal conductivity of Ar is lower than N_2 the response of the 7C cell will depend on the composition of the measured gases.

4. <u>Steady State Experiments with Water Vapor (Moisture) or Steam</u>

For the second set of steady state experiments, the apparatus was changed to include a flask in which water could be boiled and the resulting steam could be swept into the gas line entering the thermal cell by the carrier gases. A diagram of the apparatus configuration is shown in Figure 5. In addition to the steady state experiments, a measurement of the response time of the cell was performed.

In order to prevent any condensation in the gas line between the injection point and the thermal cell, heat tape was added to the copper tube between the oven and the flask. The heat tape was operated at $212^{o}F$ and the oven temperature was set at $220^{o}F$. The resulting measured gas/steam temperature entering the thermal cell ranged from $211^{o}F$ to $213^{o}F$. Because the saturation temperature at laboratory conditions (12 psia) was $202^{o}F$, the measured gas/steam temperatures ensured superheated conditions. The entire system was leak checked and the bridge current was measured to be 67.65 mA. Prior to running the elevated temperature tests, the bridge output was re-checked for span gas (100% He) and zero gas (100% N_2) conditions at nominal temperatures and no bridge balance adjustment was required.

Prior to running the steam/humidity tests, a response time measurement was made for both a sudden increase and decrease in He flow under constant N_2 flow conditions. Based on the known tube diameters and lengths, the system delay time (for He/N_2 to transport to the detector) was subtracted from the measured data to provide an indication of the response time of the detector alone. These results are shown in

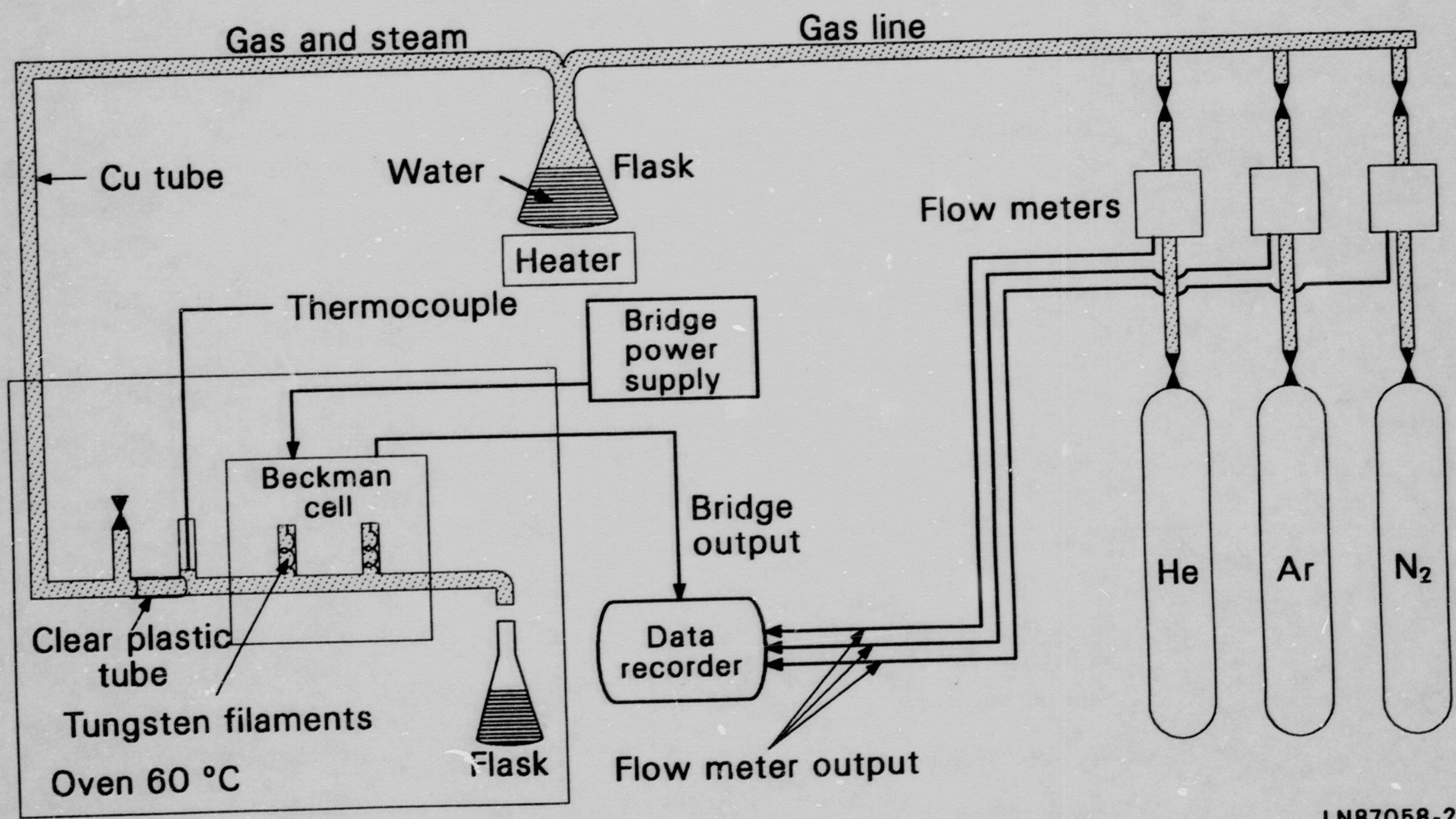

Figure 5. Diagram of apparatus used to inject steam and water vapor into the 7C thermal cell with various combinations of He/Ar/N_2 gases.

Figure 6. As can be seen from Figure 6, the measured response time for the 7C-thermal conductivity cell is within the manufacturer's suggested 95% signal change in 30 s.

During the heatup portion of the tests it was observed that the thermal cell output signal dropped as the oven and heat tape temperatures were increased at a constant N_2 flow. This observation is consistent with the fact that the heat loss from the tungsten filaments (operating at about 411^{o}F) should be proportional to the temperature difference between the filaments and the ambient gas, as well as the local heat transfer coefficient which is a function of the thermal conductivity of the gas mixture. In fact, no heat loss from the filaments, and therefore no change in bridge voltage, would occur if the input gas temperature reached the temperature the tungsten filaments.

After the desired operating temperatures were reached, the bridge output voltage was re-checked under zero gas conditions. Due to the higher than nominal operating temperatures, the bridge potentiometer had to be adjusted slightly to give 0.0 mV for N_2. After the elevated gas tests were completed, the water in the flask was allowed to boil and the effects of steam on the 7C cell were observed under constant He/N_2 flow conditions. The data are presented in Tables 6 and 7. The general observation noted during these tests was that the bridge output signal decreases markedly when steam is injected, producing a signal similar to that which occurred when Ar gas was injected. Because the thermal conductivity of steam (0.0251 W/m-K) and Ar (0.0208 W/m-K) are very similar at 366 K (200^{o}F), it appears that the drop in the 7C thermal cell output voltage is simply due to a general decrease in the thermal conductivity of the gas/steam mixture relative to the corresponding dry gas conditions.

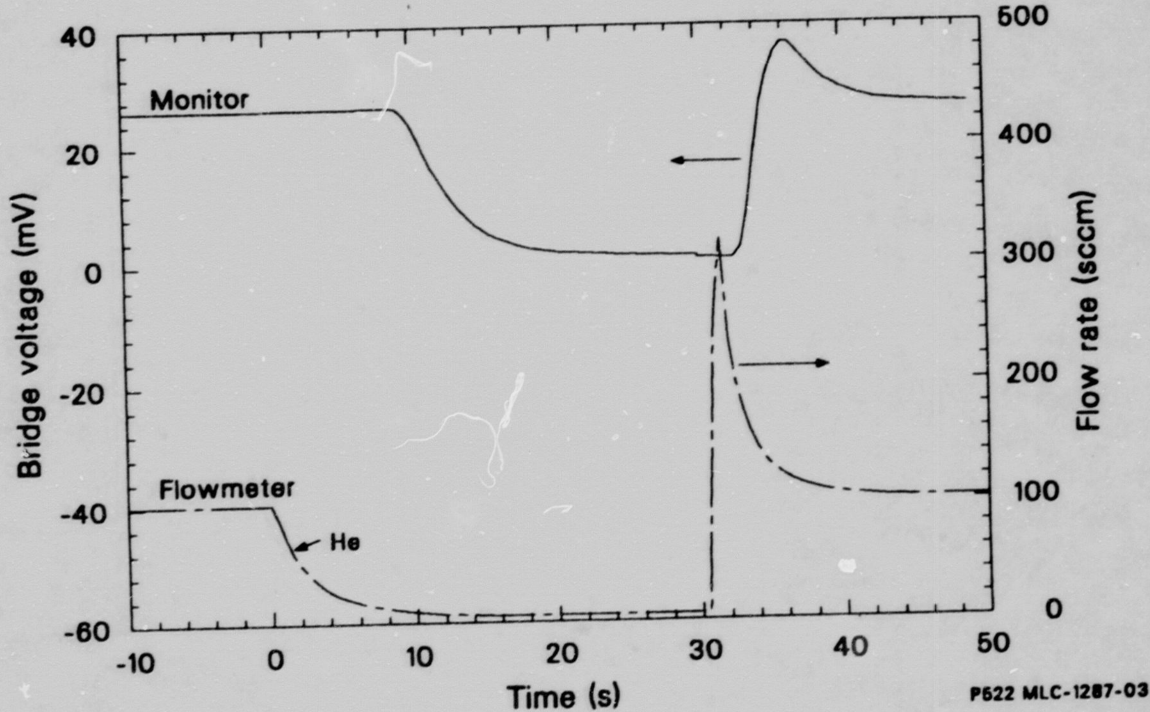

Figure 6. Response time measurement of the 7C thermal cell to changes in the He gas flow rate at a constant (191 sccm) N_2 flow rate. The sample line delay time varying from 6 to 9 s has been subtracted from the measured data to produce this figure.

TABLE 6. EXPERIMENT 6 STEADY STATE TEST RESULTS: EFFECT OF HUMIDITY AND STEAM ON THE RESPONSE OF THE THERMAL CELL OUTPUT VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Gas Temperature (F)	Bridge Output (mV)
Without steam injection				
0.0	255.4	0.0	212	0.1
98.6	190.0	0.0	211	21.8
51.4	194.4	0.0	212	14.8
124.0	122.6	0.0	213	27.6
195.7	55.4	0.0	213	35.2
50.0	151.0	51.0	213	11.6
50.0	84.6	106.0	213	9.4
50.0	43.2	154.0	213	6.9
50.0	43.0	504.0	213	-6.8
48.6	42.4	960.0	213	-13.6
0.0	133.0	0.0	214	0.5
247.0	0.0	0.0	213	33.5
50.0	206.2	0.0	213	21.2
121.1	127.0	0.0	213	24.9
200.0	46.1	0.0	213	32.6
200.0	52.0	0.0	212	33.4
With steam injection				
197.0	52.0	0.0	212	-1.0
0.0	53.0	0.0	212	-4.8

* sccm = standard cubic centimeters per minute.

a. Oven temperature measured at 220°F with input gases allowed to reach about 213°F. The bridge output was re-adjusted prior to the test to give 0.0 mV under zero gas conditions at 212°F.

TABLE 7. EXPERIMENT 7: ADDITIONAL STEADY STATE HUMIDITY TEST RESULTS.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Water|Gas Temperature (F)	Bridge Output (mV)
0.0	285.0	0.0	76|138	0.3
249.0	0.0	0.0	76|138	45.4
0.0	0.0	251.0	76|138	-22.3
49.0	200.0	0.0	76|138	16.5
49.0	199.0	0.0	158|138	15.0
49.0	199.0	253.0	146|138	2.2
49.0	157.0	52.0	140|138	13.1

* sccm = standard cubic centimeters per minute (e.g. at STP).

a. Oven temperature and heat tape temperatures maintained at 140^{o}F to 145^{o}F. Water was heated in the flask and the water vapor was allowed to enter the detector with the control gases.

5. Steady State Experiments with Water Aerosols

For the next series of experiments, $He/N_2/Ar$ gases with and without water aerosols were injected into the 7C thermal conductivity cell and the output of the bridge voltage was recorded as a function of the aerosol generator setting and gas flow rate.

The water aerosols were generated in a nebulizer situated on top of the oven about 1 m upstream of the cell. A schematic showing the general equipment arrangement for these tests is presented in Figure 7. The nebulizer setting varied from 0 to 10 in the on position with 10 being the highest setting and 0 the lowest setting. In setting 2, a small very fine mist of vapor could be seen in the vapor space of the nebulizer. In setting 5 a definite (light) fog was observed. From setting 5 to 10 the concentration of aerosol particles clearly increased to the point that at a setting of 10 the "fog" was so dense that it appeared to be opaque. In the off mode, the nebulizer was connected in the system so that the carrier gases flowed through the nebulizer vapor space but no aerosols were generated in the device. In the off position some increase in humidity is to be expected since de-ionized water was present in the nebulizer.

The results of the aerosol tests are presented in Tables 8 and 9. General observations made during the aerosol testing indicate that, under nominal steady-state flow conditions (<700 sccm), the bridge voltage tended to remain constant even though large quantities of water aerosols were observed entering the inlet tubing of the 7C cell. A clear section of plastic tubing coupled the upstream section of copper tube to the inlet section of the cell and made it possible to observe the presence of water aerosols, condensate, or liquid immediately upstream of the 7C cell. At this section, there was a clear indication of "fog" or mist suspended in the gas stream. In addition, after a short period of testing, evidence of condensation was observed on the inside wall of the oven, near the exit point of the monitor tubing. At very high flow rates of Ar (>1000 sccm), and high concentrations of aerosols (maximum setting on the nebulizer), an

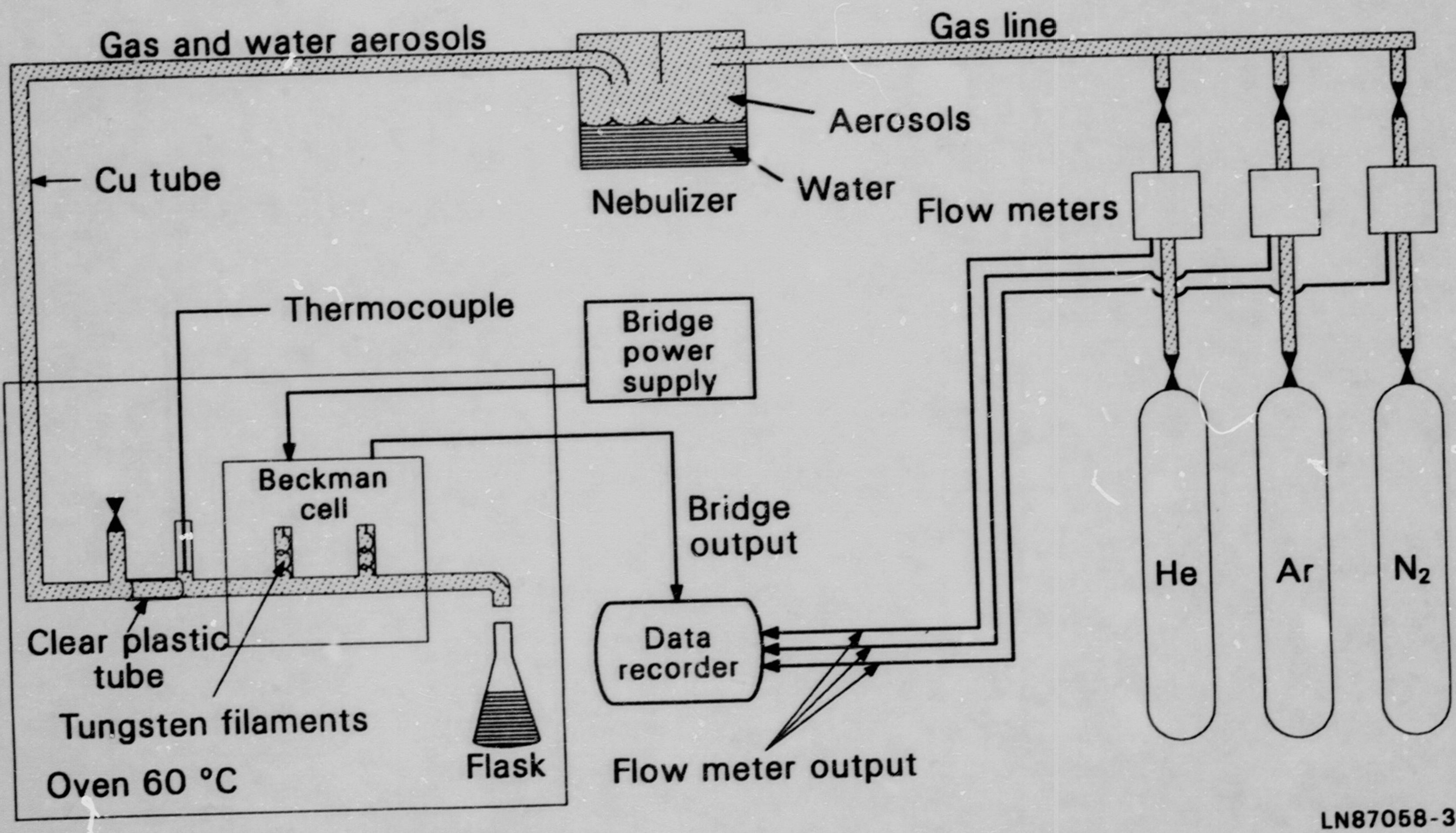

Figure 7. Diagram of apparatus used to test the effect of water aerosols on the response of the 7C thermal cell.

TABLE 8. EXPERIMENT 8: STEADY STATE TEST RESULTS WITH AND WITHOUT WATER AEROSOLS.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Gas Temperature (F) & nebulizer[b] setting	Bridge Output (mV)
0.0	254.0	0.0	136 | off	0.45
251.0	0.0	0.0	136 | off	44.6
0.0	0.0	251.0	137 | off	-21.9
0.0	0.0	251.0	137 | on 2	-21.9
0.0	0.0	251.0	137 | on 5	-21.9
0.0	0.0	> 735.0[c]	137 | on 6	-21.0
0.0	0.0	>1060.0[c]	137 | on 7	-20.5
0.0	0.0	>1060.0[c]	137 | on 9	-20.1
0.0	0.0	>1060.0[c]	137 | on 10	-16.1
0.0	933.0	0.0	137 | on 10	1.2[d]

* sccm = standard cubic centimeters per minute (e.g. at STP).

a. The oven temperature and heat tape temperatures were maintained at 142°F and 144°F respectively. Water aerosols were generated in a nebulizer and swept into the test system by the carrier gases.

b. The nebulizer setting varied from 0 to 10 in the on position with 10 being the highest setting and 0 the lowest setting.

c. The Ar flow meter for this test is over-ranged (above its calibration zone) for indicated flow rates above 700 sccm.

d. This span gas test included water aerosols.

TABLE 9. EXPERIMENT 9 STEADY STATE TEST RESULTS: EFFECT OF WATER AEROSOLS ON THE RESPONSE OF THE THERMAL CELL OUTPUT VOLTAGE.[a]

He Flow rate (sccm)*	N_2 Flow rate (sccm)*	Ar Flow rate (sccm)*	Nebulizer[b] setting	Bridge Output (mV)
0.0	245.0	0.0	off	-0.1
0.0	244.0	0.0	on 0	-0.1
0.0	244.0	0.0	on 1	0.3
0.0	244.0	0.0	on 2	0.4
0.0	244.0	0.0	on 4	0.8
0.0	251.0	0.0	on 0	0.3
0.0	251.0	0.0	on 1	0.4
0.0	251.0	0.0	on 2	0.5
0.0	251.0	0.0	on 4	0.8
0.0	251.0	0.0	on 6	0.9
0.0	251.0	0.0	on 8	0.9
0.0	251.0	0.0	on 10	0.9
0.0	933.0	0.0	on 10	1.2[c]

* sccm = standard cubic centimeters per minute.

a. The oven temperature was maintained at 142^{o}F and the inlet gas temperature measured 136^{o}F to 138^{o}F. Water aerosols were generated in a nebulizer and swept into the test system by the carrier gases. The bridge current was re-checked at cold conditions prior to testing and it measured 67.9 mA.

b. The nebulizer setting varied from 0 to 10 in the on position with 10 being the highest setting and 0 the lowest setting.

c. Water droplets were observed all along the inside of the plastic tube immediately upstream of the thermal conductivity cell.

increase in the bridge output voltage was observed from -22.1 mV to -16.1 mV (see Table 8 for detailed data). After the completion of aerosol testing, the system was shut down and allowed to cool. The piping near the 7C cell was disconnected and many small drops of water were observed inside the tube.

6. Transient Experiments

Following the steady state tests reported in Table 9, it was observed that with water aerosols and N_2 gas flowing through the thermal cell, a sudden increase in the N_2 flow rate caused the bridge output signal to behave very erratically. Tests were then performed on Ar gas for sudden increases in flow and the bridge output signal tended to increase for a few seconds before it would eventually go negative. As with the N_2 transient testing, the bridge output signal for rapid and large increases in Ar flow tended to be very noisy. The strip chart recorder was turned on and several sets of data were recorded. Figures 8 and 9 show typical responses of the system during flow surges with large quantities of water present in the test system immediately upstream of the thermal cell.

Additional testing was performed to investigate the conditions that would increase the bridge output signal. Tests were then performed for larger increases in either Ar or He flow. In every test performed with Ar, only a small increase in the bridge output was observed, even under extremely high flow conditions. Finally, a test was performed for a short transient injection of He and a completely different response was observed. Figure 10 shows the test results for a short duration, high pressure (<23 psig) He pulse. For the He case, the bridge output signal increased to about 72% of its full scale reading and then slowly drifted down to 0.0 mV after 6 minutes. Because the duration of the He pulse was very short and the bridge output response was instantaneous with the pressure pulse, it was believed that the amount of He injected into the system could not, by itself, have caused the large positive output signal. From the observed output signal, it had appeared that the thermal cell filaments had been "quenched" by water already present in the cell and that it took several minutes for the filaments to reheat to operating

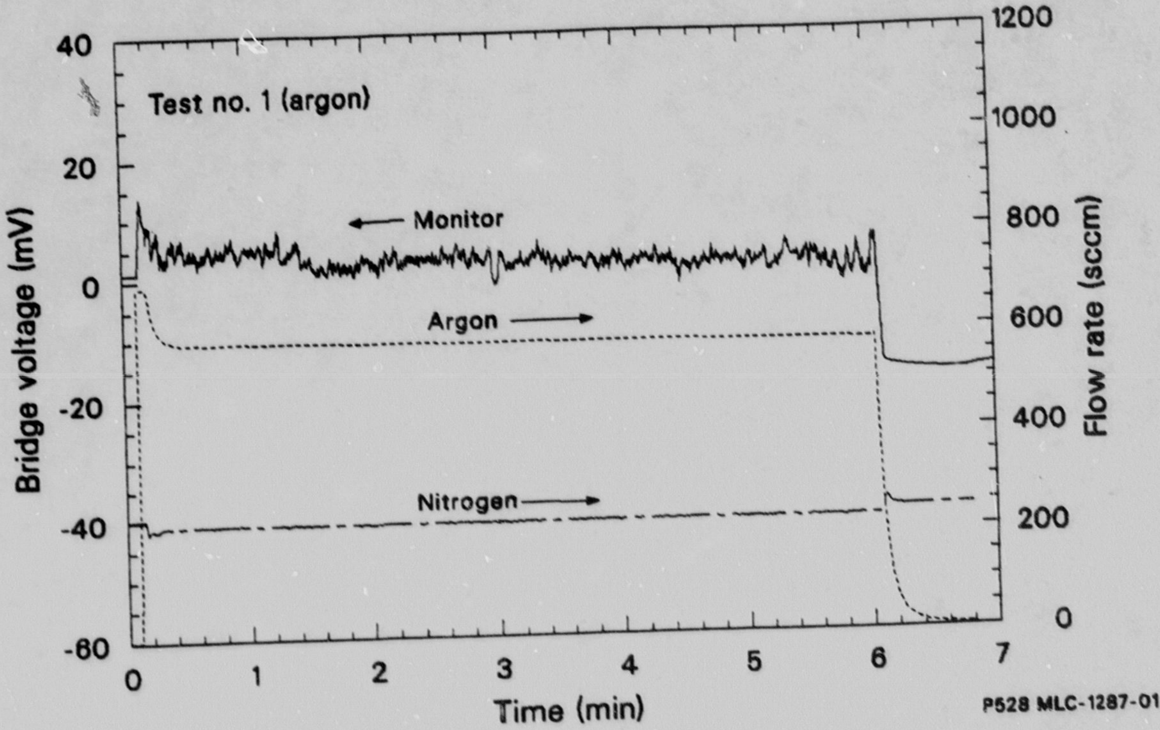

Figure 8. The 7C monitor response for a sudden increase in the Ar gas flow rate under a constant N_2 gas flow rate condition with some water present in the test system and monitor. (Transient test #1.)

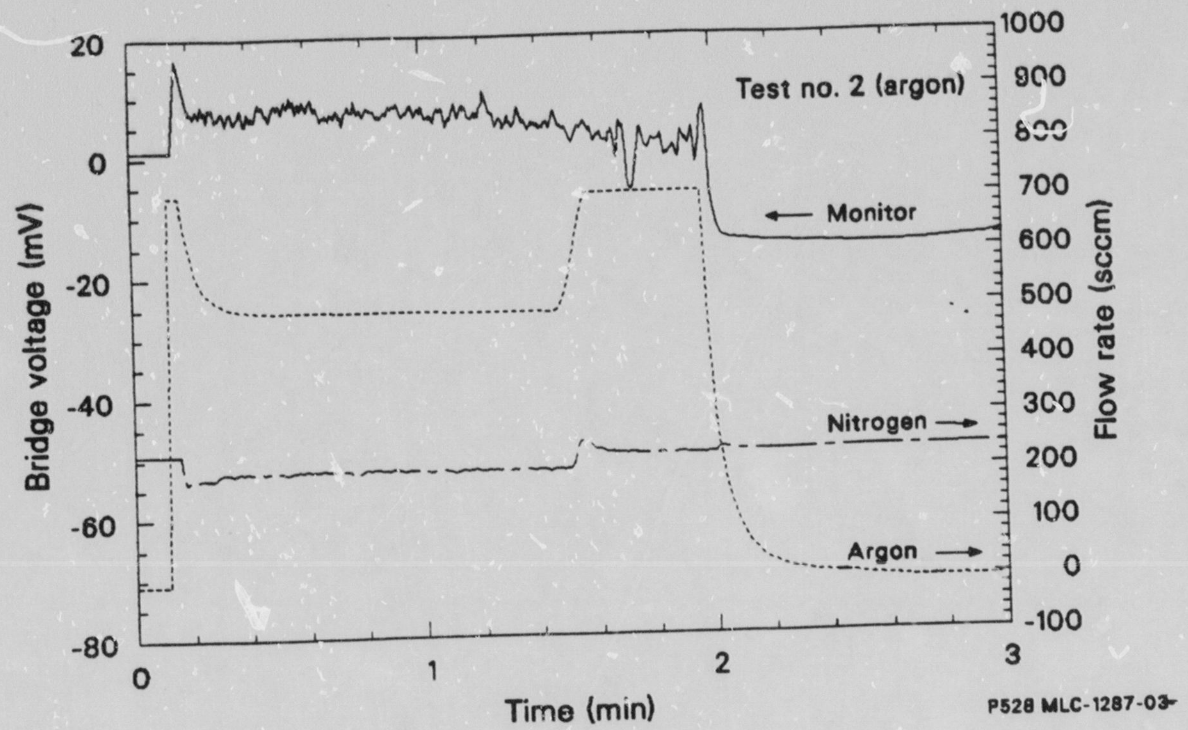

Figure 9. The 7C monitor response for a sudden increase in the Ar gas flow rate under a constant N_2 gas flow rate condition with some water present in the test system and monitor. (Transient test #2.)

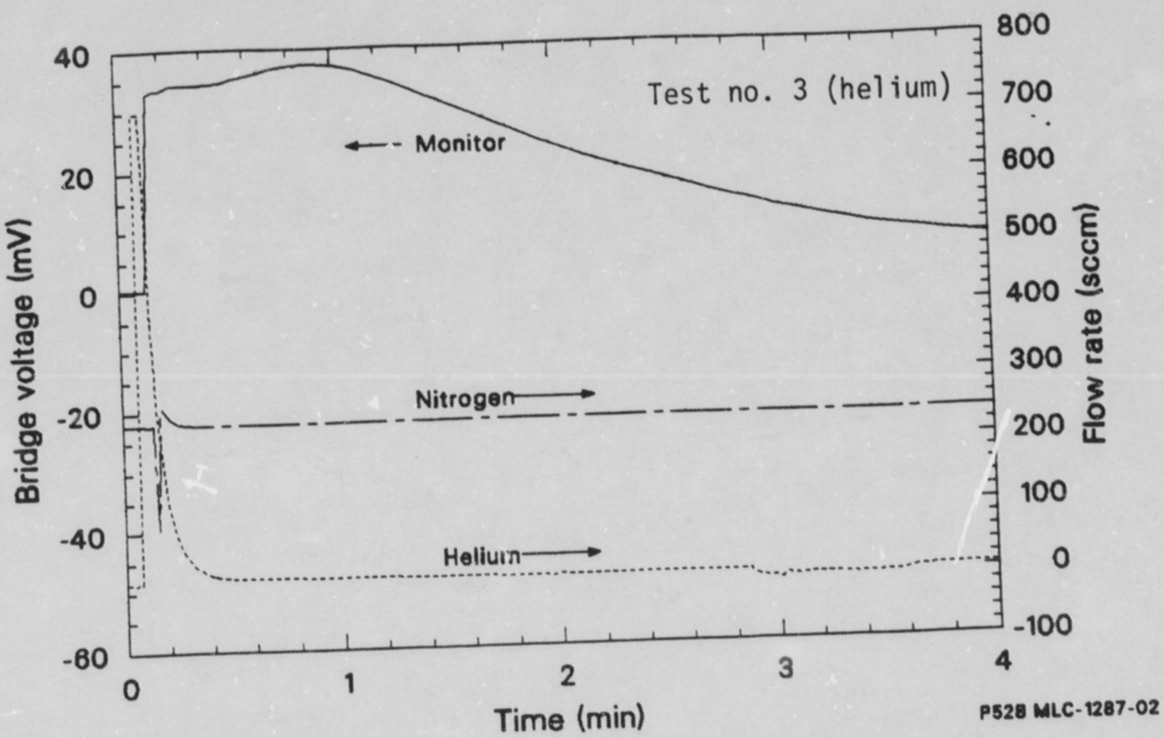

Figure 10. The 7C monitor response for a pulse increase in the He gas flow rate under a constant N_2 gas flow rate condition with some water present in the test system and monitor. (Transient test #3)

temperature again. From this data it appeared that the critical factor was not only the high flow rates but also the fact that the water was injected under pressure.

The amount of water that could be injected into the thermal cell was limited by the nebulizer output and aerosol transport down the system piping. Because the amount of water in the system could not be accurately determined, or repeated between tests, it was decided that additional tests were required whereby a known amount of liquid water would be injected into the thermal cell at moderately high pressures (1 to 15 psi). Because of the high thermal conductivity of liquid water, it was felt that this would reproduce the high output signal observed during the SFD tests. However, it was also felt that this testing would certainly destroy the tungsten filaments due to thermal or mechanical shock. Eventual testing proved that the thermal cell is much more durable than the manufacturer suggests, and the cell survived all transient testing.

The equipment layout was modified to incorporate a short piece of tube that could be filled with water and injected into the cell with a known amount of pressure. Figure 11 shows the final equipment arrangement used for the water injection tests. By filling the vertical pipe shown in Figure 11 with a measured amount of water and collecting the water in a flask that passed through the detector, it was possible to accurately control the amount of water passing through the device and repeat test results. Typical detector responses are shown in Figure 12. Based on this data it is clear that a water slug driven by a pressure pulse can result in a large positive bridge output signal. In the 10 psi case, the bridge output signal actually exceeded the instrument's full scale range. Because the output signal did not ultimately go back to 0.0mV with 100% N_2 flow, it appeared that some limited damage to the cell or filaments could have occurred. However, the bridge potentiometer could still be adjusted to balance the bridge; therefore, the instrument was utilized for future testing.

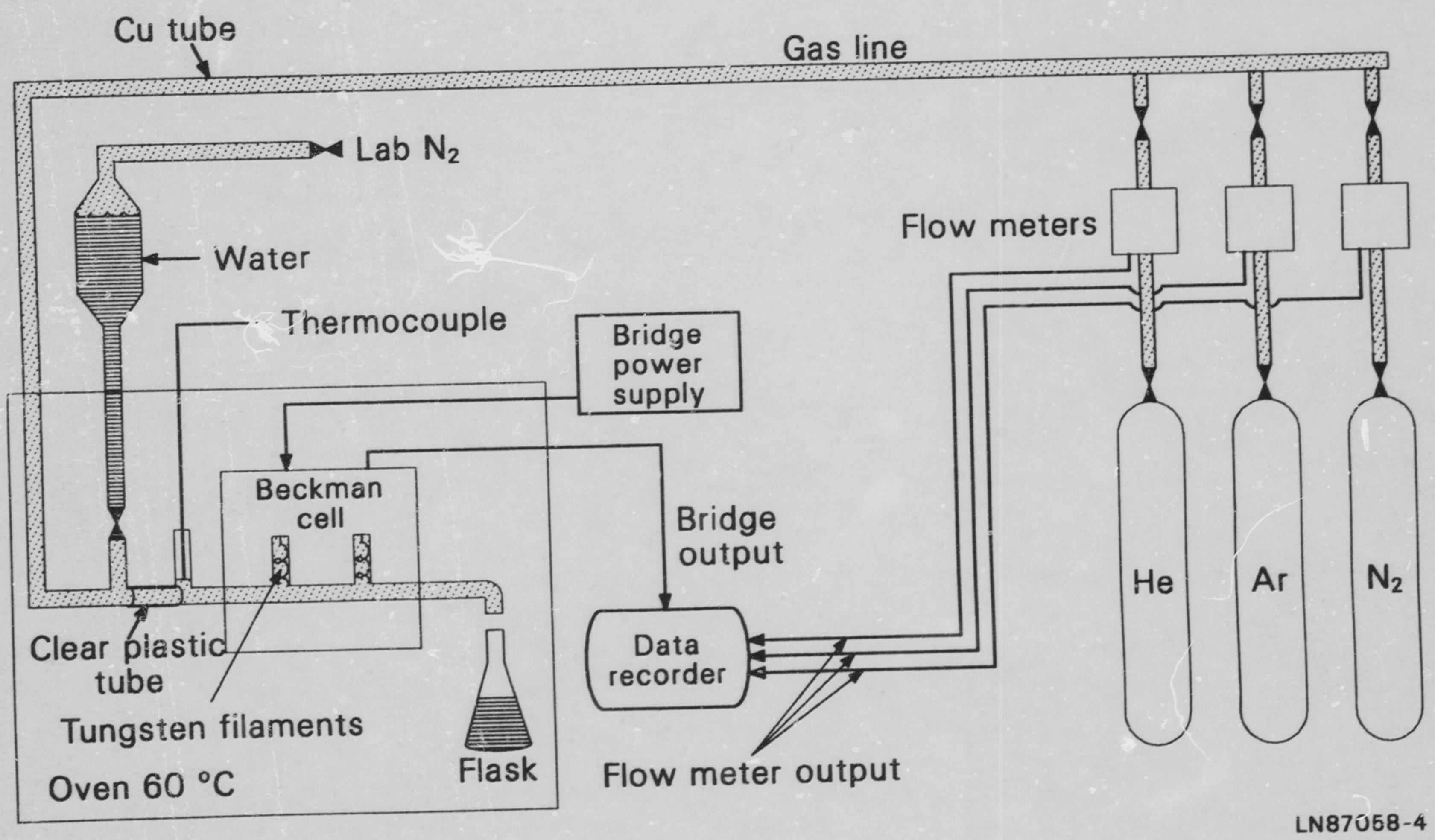

Figure 11. Apparatus used to test the response of the 7C monitor to the injection of water at different upstream pressures.

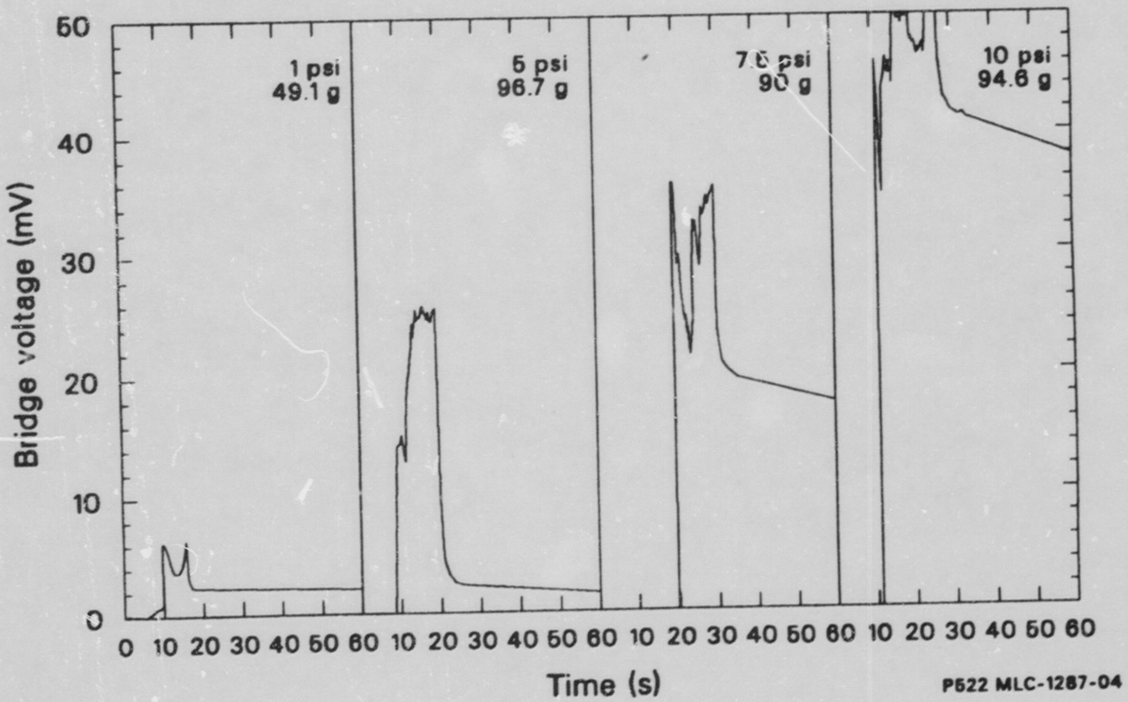

Figure 12. Bridge monitor output signal for various quantities of injected water at system pressures of 1 psig to 10 psig.

The fact that water injected into the 7C cell under steady state pressure and flow conditions does not produce a large positive output signal (even though it has a high thermal conductivity), and water injected under a pressure pulse does produce the positive signal can be explained as follows. The filaments are physically positioned at the top portion of the cell within small holes where the test gases have to diffuse in order to cool the filaments. Because water can not diffuse into these small regions (under steady state conditions), almost all of the water tends to be blown through the cell. However, when injected under pressure, water can be forced into the filament regions of the detector cell where it can "quench" or cool the tungsten filaments and thereby produce a high output signal indicative of a high concentration of high conductivity gases like H_2 or He.

7. Conclusions

The results of testing the Beckman 7 C thermal conductivity cell under various steady state and transient conditions can be summarized as follows:

Steady State Test Results:

(1) For the range of gas mixtures and flow rates tested, Ar gas tends to reduce the cell's output voltage compared to similar conditions without Ar This results because the thermal conductivity of Ar is much smaller than either N_2 or He.

(2) Increased flow rates, beyond the manufacturer's suggested 350 sccm limit but below a total flow rate of about 1500 sccm do not have a significant affect on the bridge output signal. If gas compositions are constant, then changes in gas flow rates, within the suggested manufacturer's range of 50 sccm to 350 sccm, also do not have a significant affect the bridge output voltage.

(3) As the input gas temperature is increased, the bridge output signal tends to decrease due to less heat loss from the sample gas filaments.

(4) Increases in gas humidity do not have a great effect on the bridge output signal.

(5) Injection of steam into the 7C cell reduces the output signal in a manner similar to the injection of Ar, because the thermal conductivity of Ar and steam are similar.

(6) The injection of large quantities of water aerosols (during steady state conditions) tends to increase slightly the bridge output signal (see Tables 8 and 9). However, the small increase that was observed does not account for the large positive signal that was seen during Test SFD 1-4.

<u>Transient Test Results</u>:

(1) The response time of the 7C detector is less than the 30 s value reported by the manufacturer.

(2) Pulses of Ar gas, with water in the cell, produce a short duration positive bridge output signal. The required flow rates to produce this effect are so high that similar conditions occurring during the SFD experiments is unlikely.

(3) Liquid water injected into the cell with progressively larger pressure pulses produces successively larger bridge output signals. The bridge output signals parallel those that were recorded for He. In fact, the bridge output can even exceed the designed full scale limits of the device. This particular phenomenon provides the closest explanation of the post-experiment SFD 1-4 H_2 monitor results.

8. Impact of the Hydrogen Monitor Experiments on the Interpretation of the SFD Test Data

The set of laboratory experiments have yielded valuable insight into the behavior of the monitor during the SFD tests. The results of the tests indicate that:

(1) The presence of argon reduces the monitor's signal. However, for the low mole fraction of argon in the gas line during the SFD tests, this effect is within the experimental uncertainty of the analyzer data.

(2) The analyzer is insensitive to flowrate over the range expected in the SFD tests. As a result, flow perturbations in the sampling system are not expected to affect the monitor response.

(3) The increase in the hydrogen monitor signal in all the SFD tests is the result of water being injected into the monitor under pressure. In the SFD-ST, the pressure pulse generated by reflood probably resulted in water being injected down the gasline and into the monitor. In Tests SFD 1-1, 1-3 and 1-4, the pressure pulse coincident with the argon injection to cool the bundle injected condensed water from the sampling system into the gasline and the hydrogen analyzer. Thus, it is believed that the increase in the hydrogen concentration upon cooldown of the SFD tests does not represent hydrogen generation. Data from all the SFD experiments will be modified to reflect this finding.