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HIGH TEMPERATURE TESTING OF
PRE-PRODUCTION FUEL ELEMENTS
(Title Unclassified)

By

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Experimental Engineering

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SUMMARY

Fuel elements were tested under environmental conditions simulating those encountered during reactor operations in order to study their behavior. The equipment used to obtain the simulated conditions, the developmental evaluation of some of the test components and the operation of the equipment are discussed in this report.

Typical nineteen-holed elements made of pure graphite, beaded natural uranium-graphite mixture, and enriched uranium-graphite mixtures were tested. The determination of the adequacy of the niobium-carbide coating for minimizing the hydrogen-carbon reaction was the main objective of each test, with pressure drop and heat transfer data being obtained whenever possible.

The results obtained from the tests reported here indicated an element weight loss due to hydrogen corrosion of the order of 5.0 grams during a five minute test at 4500°R element surface temperature and 550 psia hydrogen pressure at the exit of the element.

In general, the elements exhibited very little dimensional change, except in the tests in which axial expansion was restricted. In this case, the element underwent a considerable amount of bowing and maintained a permanent set in the bowed configuration. Test results indicated an axial expansion of approximately 3/8 inch when the element was heated over a 4000°F temperature difference. (This corresponds to the coefficient of thermal expansion of approximately 2×10^{-6} in. / in.-°F.)

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1.0 INTRODUCTION

In order to test fuel elements under environmental conditions simulating those encountered during reactor operation, the elements were placed in a pressure vessel and pressure and temperature conditions were varied as required.

The elements were heated by direct current resistance heating using the element as the resistance. Pressure and flow-rate were maintained by standard control systems.

The details of the facility, test loop, test operation, and test results are given in the following paragraphs.

2.0 TEST FACILITY

2.1 Test Cell and Control Room

The layout of the test cells and the control room is shown in Figure 1, with photographs of the high temperature test cell in Figure 2 and of the control room in Figure 3. These facilities are located about 40 feet behind Building 7 and face a 120 foot bluff.

Only one of the two test cells was used for high temperature flow tests, with the other used for ambient temperature testing. The floor and three side walls of each test cell are constructed of reinforced concrete of thicknesses as shown in Figure 1. The fourth side, facing the bluff, is a polyethylene film stretched over a wooden frame. The lower sections of the frame, to a height of eight feet, are removable along the entire width of the cell, to permit ready access. The roof is a corrugated plastic sheet (Resolite Type 820)

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with a blast net securely fastened above it. The cell can be viewed from the control room through two windows, each two-foot square and composed of three layers of 1-1/4" plate glass (PPG "Herculite").

Any hydrogen gas which may leak from the apparatus is prevented from stagnating in the cell by a blower system which changes the air in the cell about twenty times per minute.

The control room and rectifier room are constructed of 8" hollow concrete block with a 4" reinforced concrete roof. This building is completely separate from the test cell building, with a distance of 8" between adjacent walls. Personnel within these areas are protected in the event of an explosion because the construction of the cell insures that any blast would be directed away from the control room and toward the hillside. Access to the open side of the test cell is limited by a twelve foot link fence. Access to the general area while a test was in progress was limited by barricades and flashing red warning lights.

2.2 Gas Supply

Gaseous hydrogen was supplied for testing by a tube trailer which was parked to the north of Cell #1. This trailer had a supply of 60,000 standard cubic feet of hydrogen at an initial pressure of 2200 psig. Helium gas was supplied by a 120 bottle bank of standard bottles which was recharged by truck as required. Nitrogen gas was supplied by a 20 bottle bank which was recharged by changing bottles.

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2.3 High Bay and Vault

A high bay area in the rear of Building #5 is used for disassembly, cleaning and repair of the furnace and heat exchanger. Graphite and natural fueled elements are also stored in this area. Adjacent to this is a vault area in which a maximum of twenty enriched fueled elements can be stored. These areas are treated as contaminated, with personnel required to wear shop coats, gloves, and shoe covers.

2.4 Element Measuring Equipment

All measurements on the elements were done within the vault area. A scale with a 2000 gm capacity was used to determine the element weight before and after a test. The scale is marked in divisions of one gram with the nearest tenth of a gram estimated. A fixture equipped with dial gauges was used to measure the length and bow of each element before and after a test. An ammeter and voltmeter were used to determine the resistance of the element at six inch intervals along its entire length. The distance across flats was measured with a micrometer at five positions along the element length. The diameter of each flow channel was determined by means of a Sheffield "Precisionaire" gauge at a distance of one inch and eight inches from each end. This device measured the diameter by means of a calibrated air flow.

3.0 TEST LOOP

The test loop consists of the furnace, connector, and heat exchanger, along

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with gas, water, electrical, and instrumentation systems which contain all necessary components for operating and monitoring during corrosion testing.

Figure 4 shows the horizontal, water cooled pressure vessel with the fuel element mounted in graphite chucks in its center. There are nine viewports which permitted observing the element during testing for determining element surface temperature.

Gaseous hydrogen flowed through the holes of the fuel element and an inert helium atmosphere was maintained on the outside of the element. Helium and nitrogen were used for purging the loop before and after testing. Figure 7 shows these gas systems with the various valves that control their use.

After the hot gas left the element it was discharged through a connector and transition section into a heat exchanger for cooling to a temperature compatible with filtering. This was necessary to prevent contaminated corrosion products from entering the atmosphere. The transition section and heat exchanger are shown respectively in Figure 5 and 6.

The furnace, connector, and heat exchanger were all water cooled by the system shown schematically in Figure 8. Three hundred gpm at a pump discharge pressure of 300 psig are available for this purpose. Orifices are provided in the outlet lines from the various parts of the furnace, connector, and heat exchanger to meter the flow for heat balance determination. The water system is a closed loop with the supply provided by a 10,000 gallon pool.

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The instrumentation system consists of the control equipment and the read-out meters and recorders. Figure 3 shows the meter panels and control console and indicates the information obtained by this instrumentation. Figures 7 and 9 show these instruments schematically. Gas flow measurements were obtained by sharp edged orifices in conjunction with pneumatic differential transmitters. The flow rates obtained by this system were checked against pressure-time data from the hydrogen gas cylinders. Close agreement was obtained between the calculated flow rates and that indicated by the orifice pressure drop actuated instrumentation. Gas pressure was measured by direct reading bourdon tube type gauges and by pneumatic instrumentation which sent a pneumatic signal proportional to pressure to receiver gauges in the control room. These signals were also used with pneumatic controllers for automatically controlling the pressure at the desired set point. The flow signals from the pneumatic differential transmitters were also sent to pneumatic controllers for automatically maintaining the flow according to preset rates. On the top of the furnace are five viewports designed for use with Radiamatics, the Honeywell name for a thermopile, which were used to send signals to a recorder to record the element temperatures. An optical pyrometer was used with the four viewports on the side of the furnace for element temperature measurements.

The elements were heated to the specified temperature by electric resistance heating using the element as the resistance. The electrical power for this resistance heating was provided by a 2.8 MW direct current power supply. 25,000 volts A. C. were fed to the site by West Penn Power Company

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as shown in the block diagram in Figure 10. This power was received through a pole-top manually-operated air break switch and transferred through high voltage fuses to a 3750 KVA 25/4.16 KV transformer. The 4.16 KV then went through disconnect switches, fuses, and metering equipment to the outdoor switchgear. The outdoor switchgear contains the protective relays, indicating meters, and the 50-DH-75 circuit breakers which functioned as a main contactor as well as overcurrent protection. From the switchgear the power went to a 1600 KVA induction regulator which either bucked or boosted the 4.16 KV supply voltage. The output of the induction regulator, which can be varied continuously from 480 to 7840 volts, was fed to the primary windings of two rectifier transformers. Each transformer has two parallel double wye secondary windings which feed two six phase water cooled silicon rectifiers. Each rectifier has a rating of 8750 amperes at 80 volts. High current switches on the roof of the test cells are arranged to connect the four rectifiers in series, series-parallel, or parallel. This output was then fed to the 35,000 ampere water cooled bus leading into test cell no. 2. Water cooled flexible cables are connected between the bus and furnace. The induction regulator can be varied at such a rate that a 320 volt change can be obtained in 15 seconds.

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4.0 TEST EQUIPMENT DEVELOPMENT

4.1 Chuck Design

The element supports, or chucks, were a design problem during the early phases of the test program. The problem was to design the chucks to perform three simultaneous functions:

1. Provide electrical contact between the element and the furnace electrodes.
2. Provide a gas seal between the hydrogen coolant and the helium atmosphere.
3. Allow thermal expansion of the element.

Initially, the chucks were either solid or split versions of the type shown in Figure 11. The solid chuck fulfilled the gas seal requirements but lacked the mechanical flexibility to maintain good electrical contact throughout the entire operating temperature range and to permit thermal expansion of the element in the radial direction. The split version provided the required flexibility but afforded no gas seal. Both versions were firmly secured and allowed no thermal expansion in the axial direction. Also, being rigidly aligned, the chucks allowed no way of relieving any bowing of the element due to thermal expansion. A high percentage of the elements tested with this type of chuck failed due to excessive bowing and/or electrical arcing.

The second type of chuck, shown in Figure 12, was a tapered insert chuck which was tried in an attempt to improve the gas seal. The tapered chuck, however, allowed little, if any, bowing and many elements failed due to flexural stresses.

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A third type of chuck was developed in the form of a ball-and-socket arrangement, Figure 13. The purpose of that arrangement was to provide a gas seal and a flexible mounting at the same time. Some success was achieved with the ball-and-socket chuck, but many elements failed because of restricted thermal expansion in the axial direction.

A fourth arrangement was used in the form of a spring loaded, sliding chuck at the cold inlet end of the furnace, in combination with various forms of the three previous chucks at the hot outlet end. Stationary chucks at the outlet provided a gas seal at that end; the sliding chuck at the inlet allowed unrestricted thermal expansion in the axial direction. The sliding chuck was successful on the first try and was used almost exclusively thereafter at the cold end of the furnace. Various refinements were added to the sliding chuck to suppress electrical arcing and to allow a controlled gripping of the element. The latest version is shown in Figure 14.

Electrical cables provided extra current carrying capacity to suppress arcing at the sliding surfaces, while a threaded, tapered insert provided a means of positively gripping the element to provide good electrical contact between the chuck and the element. A solid chuck was used at the hot outlet end in the latest installation, but was held stationary in order to provide a gas seal at that end. The chuck used at the outlet end was similar to the solid version, Figure 11.

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4.2 Element Temperature

Measurement of the element surface temperature involved mainly the problem of calibrating the visual optical pyrometer used to measure radiation temperatures. The element radiation passes through a viewport lens, through a system of reflecting prisms, and finally through the windows between the test cell and the control room. Absorptivities in the path described were determined by comparing the temperature readings of a wide tungsten filament incandescent lamp viewed directly, with readings obtained by observing this standard lamp through the system of windows, prisms and viewport. The results are shown in Figure 15.

Radiation temperature data for the standard lamp was obtained from Temperature - Its Measurement and Control in Science and Industry, Vol. 3, Part I, (1961.) When testing an element, power was applied to the element until the visual pyrometer reading reached a "thru glass" temperature corresponding to the desired true element temperature.

In addition to the visual pyrometer, element temperature was also measured by Radiamatics mounted on the top furnace viewports. The Radiamatics readings are recorded on strip charts to provide a continuous indication of element temperature.

Temperature readings obtained by the visual pyrometer and by the Radiamatics are radiation temperatures for the element surface, however, and do not necessarily represent either the maximum element temperature or the mean

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temperature through a given cross-section. A study is now being made to determine the maximum temperature within the element, based on the measured surface temperature and the calculated heat transfer rate at the surface.

4.3 Gas Temperature

Measurement of the gas temperature at the outlet of the element has been attempted by use of a Tungsten, Tungsten -26% Rhenium thermocouple inserted into the gas stream at the position shown in Figure 5. However, the measurement of gas temperature of the magnitude (4000-4500 °F) encountered in these tests is extremely difficult. Since the thermocouple temperature is the equilibrium value attained as a result of the heat transferred by convective means from the gas stream and the heat lost by radiation and conduction to the surrounding water-cooled walls, the thermocouple will always indicate a temperature lower than that of the gas stream. The relatively slow velocity of the hydrogen after it has emerged from the element, together with the water-cooled walls, combine to produce a very large difference between the gas and thermocouple temperatures.

To avoid such large errors, a water-cooled, series orifice gas probe is being fabricated. This device, described in NACA TN 2167 (September, 1950), is expected to give temperature readings within 6% of the true gas temperature. Also, in an attempt to decrease the radiation loss from the present thermocouple, a graphite shield was placed in the connector. This has reduced the temperature error by about a factor of two.

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5.0 TYPICAL TEST OPERATION

5.1 Fuel Receiving

Fuel elements were received from the Materials Department in aluminum containers and stored in the hydrogen corrosion fuel vault after being logged and measured as discussed in Section 2.4.

5.2 Furnace Loading

A single fuel element was removed from the fuel vault, carried to the hydrogen corrosion test facility, and loaded into the hydrogen corrosion furnace. The loading procedure includes the proper fitting of the graphite support fixtures to the fuel element.

5.3 Hydrogen Corrosion Test Loop Check-Out

After the element was loaded and the furnace closed, the test loop gas system was evacuated, then pressurized with helium and checked for gas leaks. At the same time, the water cooling system was started, adjusted for proper coolant distribution, and checked for leaks.

5.4 Element Testing

When check-out was complete, the fuel element was tested under specified conditions of temperature, hydrogen pressure, hydrogen flow rate, and test duration. The sequence of steps involved was as follows:

- a. Purged system with helium.
- b. Introduced hydrogen to the system.
- c. Brought hydrogen up to the desired pressure and flow rate.

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- d. Applied electrical power in a series of step functions until desired power level was reached. The step function consisted of 50-volt steps applied ten seconds apart. The voltage increase was controlled at a rate of twenty volts per second. This required 2 1/2 seconds for each voltage increase, leaving 7 1/2 seconds stabilization time in each ten second interval.
- e. Maintained all parameters of hydrogen pressure, hydrogen flow rate, and electrical power input constant during the run.
- f. After specified power duration was complete, decreased power in a series of step functions with the same time schedule as Part d.
- g. Reduced system pressure and began helium purge.
- h. Followed helium purge with a nitrogen purge.
- i. Shut off all systems.

5.5 Post-Test

The fuel element was removed from the furnace, inspected for any structural flaws, then logged and measured as described in Section 2.4. Element weight loss, if any, was recorded on the test summary, Appendix A.

5.6 Fuel Disposition

At various intervals, the tested fuel elements were removed from the hydrogen corrosion fuel vault and returned to the Materials Department via the hydrogen corrosion fuel custodian and the hydrogen corrosion building fuel accountability representative.

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6.0 TEST RESULTS

There have been 100 tests performed to date. The initial tests were equipment checkout runs used primarily to obtain information on the response of the system. As the test procedures became firm, emphasis was directed toward obtaining meaningful data from fuel elements.

The first ten tests were at low temperatures (Max. 2570°R) with long power ramp times (Max. 28 min.). These tests provided information on the characteristics of the test facility control system.

Tests 10-20 were at higher temperatures (Max. 4060°R) with the elements in several tests remaining at maximum temperature for reasonable periods (3-5 minutes). Problems in the graphite chucks for holding the elements were noted as well as failures in elements. The causes of these difficulties were studied and changes in procedures and equipment were made to improve testing reliability.

The major problem at this time was arcing of the chucks and tests 20-50 represent the chuck development period. Desired test temperatures were reached but a number of elements failed at the upstream (cold end) chuck. These failures appeared to be chuck failures and so a number of modifications were made which resulted in a sliding chuck which tightly gripped the element and transferred power by copper pigtails. This arrangement has proved most satisfactory.

Tests 50-60 generally were conducted with natural fueled elements.

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Failures due to test equipment were very few and the elements were beginning to survive a five minute test although weight loss was fairly high.

Tests 60-70 again showed a higher percentage of the elements surviving the five minute test with failures being at the hot end and attributable to corrosion as indicated by high weight loss.

Tests 70-80 generally were conducted with enriched fueled elements with those tested at 4500 °R usually surviving the five minute test. High temperature tests (4900 °R) generally resulted in failure within three minutes with excessive weight loss.

Tests 80-100 were predominately enriched-fuel elements. The 4500 °R tests were generally successful, with some successful tests also obtained as the temperature was progressively increased in 100 °R steps up to 4900 °R. The weight loss increased with temperature, with the elements tested at 4900 °R still showing failure within three minutes. Figure 16 shows the relationship between weight loss and temperature obtained from all five-minute tests with coated, enriched-fuel elements.

As the test program progressed and the various mechanical problems were solved, more time was available during each test for measuring the element surface temperature at several points along the element. A typical axial temperature profile measured during these tests is shown in Figure 17.

The summary of the first 100 tests is given in Appendix A.

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7.0 CONCLUSIONS

The test results discussed previously have resulted in a continual upgrading of the test equipment and testing techniques until consistent and reproducible information can now be obtained. This level of competence will permit more effort to be devoted to increasing the accuracy and number of the measurements which can be made during each test.

The fuel elements have shown a continual improvement, based on their ability to survive the test period with acceptable weight loss. A detailed analysis of the elements with respect to their status for reactor use is carried out as part of the Materials Department program.

8.0 FUTURE WORK

Future hydrogen corrosion testing will be divided into the following four areas:

1. Single element tests for statistical analysis.
2. Single element tests for material analysis.
3. Single element tests for heat transfer analysis verification.
4. Support block-tie rod flow and thermal gradient tests.

8.1 Statistical Analysis

A percentage of the elements from each niobium-carbide coating batch is to be hydrogen corrosion tested as part of the quality control program. The entire coating batch will be accepted or rejected depending on the weight loss and overall condition of an element after testing. Tentative plans call for

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the element to be tested for five minutes at 4452°R with a hydrogen exit pressure of 560 psig and flow of 500 SCFM. The maximum allowable weight loss without chemical analysis will be 3-4 grams. If the weight loss exceeds this value, chemical analysis will be required to establish that the element has maintained the desired nuclear reactivity and also to determine whether the losses are uniform within 10% along the length of the element.

8.2 Materials Analysis

Concurrent with the quality control testing will be the materials development program. The purpose of this program is to study corrosion behavior at temperatures higher than 4452°R . It is expected that the quality control test temperature will be raised as the materials development program progresses.

8.3 Heat Transfer Analysis

During all of the tests discussed above heat transfer and pressure drop information will be obtained whenever possible. But in addition to this work additional tests will be performed specifically for studying these areas for the purpose of obtaining data that can be used to verify the heat transfer computer program.

8.4 Support block Tests

In addition to the single element hydrogen corrosion tests, support block tests will also be performed. These tests consist of determining the corrosion

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effects of the hot gas on the support blocks, determining the maximum thermal gradients that can be expected in and/or withstood by a support block, and determining the tie rod button temperatures. The support blocks will be placed at the exit end of the single element furnace thus permitting use of the single element facilities for these tests.

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APPENDIX A

SUMMARY OF FUEL ELEMENT TESTS

1 - 100

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Run	No. Element	Descrip- tion	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
* 3	545	Graphite	333	200 (H ₂)	-	-	-	2700	1500	60	- ' - min " - sec	- ' - min " - sec	-	Element showed some pitting and bowing after test.
4	42-673	Graphite	100	-	550	-	8	-	2500	180	28'	0	-	Routine test.
5	1073	Coated	500	-	550	-	0	-	-	150	6'	0	-	Upstream chuck broke.
6	1074	Coated	330	-	-	-	-	520	520	0	-	-	-	Cold flow.
7	1074	Coated	500	-	-	-	-	520	520	0	-	-	-	Cold flow.
8	1134	Coated	217	575	550	25	42	2260	1700	112	20'	4'	.1	No apparent change in element.
9	1135	Coated	300	-	470	-	0	2570	2100	170	17'	-	-	No apparent change in element.
10	1128	Coated	166	-	-	-	-	520	520	0	-	-	-	Cold flow.
11	1135	Coated	500	560	500	60	0	3960	3000	330	18'	-	-	Downstream chuck eroded away.
12	3601	Coated	0	-	-	-	-	-	-	0	-	-	-	Aborted due to leak during evacuation.
13	3601	Coated	0	-	-	-	-	-	-	0	-	-	-	Aborted due to high H _e flow.
14	3601	Coated	500	570	480	90	0	4060	3500	397	5'	4'	5.2	Arcing observed during the run. No damage to element.

* Runs 1 and 2 were calibration runs.

Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
15	3607	Coated	500	560	478	82	0	4060	3500	397	5'	4'	6.6	Element broke midway.
16	3602	Coated	500	560	470	90	0	4060	3400	436	2'	3'40"	-	Element broke into 4 pieces
17	3692	Coated	250	-	-	-	-	-	-	0	-	-	-	Aborted due to defective solenoid.
18	3692	Coated	250	550	530	20	0	3000	2000	200	15'	29'30"	7.7	Element showed high corrosion due to H ₂ in furnace atmosphere.
19	3695	Coated	250	570	540	30	25	3640	2100	206	5'	5'	.3	Element remained intact.
20	3695	Coated	250	550	-	-	25	-	-	110	6'30"	-	-	Aborted due to arcing at 120 volts at upstream chuck.
21	3695	Coated	250	550	515	35	21	4320	3700	321	7'	4'	3.4	Element snapped.
22	3717	Coated	250	550	500	50	12.5	4560	-	300	4'30"	2'45"	43.6	Element eroded at downstream chuck.
23	808	Coated	250	550	500	50	42	5200	3500	500	4'45"	15"	10.7	Element apparently eroded.
24	3696	Coated	250	550	500	50	42	4600	3500	468	3'15"	30"	28.1	Element eroded at downstream chuck.

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
25	853	Coated	170 (H _e)	(H _e)220	(H _a)200	20	-	4700	2700	140	2'15"	10"	2.3	Element remained intact.
26	-	-	-	-	-	-	-	-	-	-	-	-	-	Pyrometer Calibration.
27	-	-	-	-	-	-	-	-	-	-	-	-	-	Aborted due to leak in inlet plenum.
28	853	Coated	250	570	530	40	0	4600	3000	340	3'45"	3'45"	6.1	Element failed at up- stream chuck.
29	785	Coated	250	555	500	55	25	4650	-	300	3'45"	2'45"	-	Element failed at three points.
30	799	Coated	330	550	490	60	25	4460	3600	400	5'15"	45"	1.2	Element failed in two places close to upstream chuck.
31	796	Coated	330	560	455	105	42	4610	-	440	4'	1'45"	17.3	Element failed at both ends.
32	795	Coated	330	535	440	95	42	4560	3000	400	1'30"	5'	2.4	Element re- mained intact but arced at upstream end.
33	794	Coated	500	580	470	110	42	4500	3400	570	1'	45"	-	Element failed at upstream end.
34	AC-09 4728	Coated	500	570	450	120	42	4320	2500	480	45"	3'	2.1	Element failed at cold end.
35	1074	-	-	-	-	-	-	-	-	-	-	-	-	Pyrometer check.

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	A P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
36	AC-09-4740	Coated	500	550	440	110	0	4300	3360	507	45"	3'-0"	-	Spring loaded chuck - element broke at cold end.
37	-	-	-	-	-	-	-	-	-	-	-	-	-	Power supply failure.
38	AC-09-4744	Coated	500	550	440	110	38	4420	3300	576	-	15"	5.0	Long sliding chuck on cold end-MSA shut-down and broken element
39	AC-09-4724	Coated	500	550	400	150	42	4320	3300	620	12"	2'-21"	7.8	Long sliding chuck on cold end-cracked on cold end-broke at hot end.
40	2798	Natural fueled coated	500	540	385	155	42	4100	3500	555	1'-0"	5'-0"	1.5	Spring loaded chuck at cold end. Arcing at cold end, but no breakage.
41	2832	Natural fueled coated	500	540	370	170	41	4500	3900	620	1'-30"	5'-0"	2.6	Long sliding chuck-bolted to element. Arcing on chuck, but not element.
42	2840	Natural fueled coated	500	550	390	160	42	4140	3200	515	1'-0"	5'-0"	1.1	Spring loaded chuck-element was unmarked.
43	2840 re-run	Natural fueled coated	500	720	550	170	42	4500	3900	638	1'-0"	30"	3.1	Spring loaded chuck-element broke.

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
44	AC-09 890	Coated	500	-	-	-	-	-	520	-	-	-	-	Failure in power supply.
45	AC-09 3782	Coated	500	-	-	-	-	-	520	-	-	-	-	Cold flow.
46	AC-09 3782	Coated unfueled	500	570	550	20	41	-	1960	180	45"	----	4.5	Element badly arced at 2-3/8" & 4-1/4". Run aborted due to arcing.
47	AC-09 890	Coated Unfueled	500	600	550	50	41	---	3800	750	2'	---	14.2 14.7T**	Element broke at upstream chuck.
48	AC 09 4721	Coated Unfueled	500	620	550	70	41	---	---	532	1'	---	6.4 21.1T	Element broke in downstream chuck (ball)
49	3809	Natural fueled coated	500	600	540	60	41	4260	3460	580	45"	2'	5.0 26.1T	Element broke in upstream chuck.
50	AC-09 4723	Coated Unfueled	500	570	550	20	41	-----	---	---	-----	-----	0 26.1T	Run aborted, upstream chuck slid forward, no power.
51	2793	Natural fueled coated	500	690	560	130	41	4510	3100	630	1'20"	9'10"	2.0 28.1T	Run completed. Element showed corrosion at hot end.

** T indicates total weight loss ΔW since last decontamination of furnace system.

Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H ₂ Flow (SCFM)	T Element (°R)	T Gas (°R)	Power Input (KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
52	AC49 2806	Coated Natural	500	685	555	100	42	4260	3060		1' 10"	5' 1'	4.5 32.6	Run completed. Element slight arcing downstream ball.
53	59-4054	Coated Natural	500	690	550	140	42	4460	3400	649	1' 40"	5'	10.0 42.6 T	Run completed. Element remained intact.
53B	59-4054	Coated Natural	500	825	570	255	45	4440	3400	627	1' 40"	5'	42.6 T	Element broke 1" inside downstream chuck.
54	AC99 4235	Coated Natural	500	790	550	240	42	4500	3400	627	1' 40"	2' 20"	7.0 49.6 T	Element broke at face of downstream chuck.
55	AC-69 3180	Coated Natural	500	560	-	-	42	-	2660	.649	1' 40"	10"	7.0 56.6 T	Element broke at downstream chuck.
56	2810	Coated Natural	500	560	550	10	33	-	-	616.1	1'	25"	15.0 71.6 T	Element arced and broke at 2" O.S.N. end.
57	AC09 4722	Coated Unfueled	500	650	550	100	41.6	4500	-	580	1' 20"	5'	10 81.6 T	Element broke after power run.
58	AC99 6100	Natural Fueled Coated	500	640	555	85	41.6	4500	-	515	1' 35"	4' 48"	24.5 106.1 T	Element arced and broke at downstream chuck.
59	AC99 6091	Natural Fueled Coated	500	650	550	100	41.6	4500	3060	562	1' 25"	2' 30"	1.0 107.1T	Element survived

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
60	AC 09 06233	Coated Unfueled	500	610	550	60	0	3160	2200	510	1'10"	2'20"	3.0 110.1T	Element sur- vived. Run aborted due to low pyrometer reading.
61	AC 99 4880	Coated Enriched	500	680	560	120	60	5120	—	742	1'45"	4'	46.0 156.1T	Element broke in four pieces
62	AC 99 4902	Coated Enriched	500	650	550	100	41.6	4630	2860	578	55"	6'	6.5 162.6T	Element survived
63	AC 09 04771	Coated Unfueled	500	650	550	100	41.6	4580	2920	570	42"	5'10"	3.5 166.1T	Element survived
64	AC 09 06228	Coated Unfueled	500	680	550	130	41.6	5260	3200	713	48"	12"	25.0 191.1T	Element failed at hot end.
65	AC 09 06234	Coated Unfueled	500	650	550	100	41.6	5000	3280	715	1'	2'	18.0 209.1T	Element failed at hot end.
66	AC 09 02812	Natural Fueled Coated	500	650	550	100	41.6	4440	2820	530	1'5"	7'37"	6.0 215.1T	Element failed at hot end.
67	5-1747	Natural fueled coated	500	650	550	100	41.6	4440	2860	540	1'25"	5'	3.0 218.1T	Element Survived
68	AC-09 4655	Coated Unfueled	500	645	550	95	41.6	4530	2730	572	1'15"	2'55"	18.0 236.1T	Element failed at hot end
69	AC-09 5364	Coated Unfueled	500	660	540	120	41.6	4920	2260	600	40"	5C	28.0 264.1T	Element failed at hot end
70	AC-09 5365	Coated Unfueled	500	660	550	110	41.6	4980	---	610	45"	30"	18.5 282.6T	Element broke in 3 pieces
71	AC-99 4234	Natural fueled coated	500	620	570	50	41.6	3860	2210	396	1'30"	5'	2.0 284.6T	Element Survived

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
72	AC-99 4232	Natural fueled coated	---	---	---	---	---	---	---	---	---	---	1.0 285.6T	Element failed under gas shock
73	AC-05 5367	Coated Unfueled	500	600	500	100	41.6	4960	2840	600	40"	2'59"	30.5 316.1T	Element failed at hot end
74	AC-69 3179	Natural fueled coated	500	575	475	100	41.6	4948	2890	660	1'10"	15"	9.0 325.1T	Element failed at hot end
75	AC-09 5369	Natural fueled coated	500	575	500	75	41.6	4960	---	605	40"	1'5"	24.0 349.1T	Element failed at hot end
76	AC-99 4310	Coated Enriched	500	600	500	100	41.6	3880	2200	377	45"	5'	1.5 350.6T	Element Survived
77	AC-99 4865	Coated Enriched	500	650	550	100	70.8	4440	2640	529	1'10"	5'	1.5 352.1T	Element Survived
78	AC-99 04438	Coated Enriched	500	700	550	150	66.6	4890	3120	684	1'10"	2'50"	26.5 378.6T	Element Survived
79	AC-99 07918	Coated Enriched	500	650	550	100	66.6	4840	---	667	1'5"	2'	2.0 380.6	Element Survived
79-A	AC-99-0 7918	Coated Enriched	500	740	550	190	66.6	4960	3010	667	1'	18"	18.0 398.6	Element failed at six places
80	AC-99-0 4442	Coated Enriched	500	650	550	100	66.6	3920	2520	475	1'	5'	0.5 399.1	Element Survived.
81	AC-99-0 5108	Coated Enriched	500	600	550	50	33	4460	2520	478	40"	1'45"	14.5 413.6	Element failed at hot end
82	AC-99-0 5121	Coated Enriched	500	660	550	110	70.8	4500	---	605	1'10"	5'	2.0 415.6	Element Survived
83	AC-99-0 5143	Coated Enriched	500	650	550	100	70.8	4980	3310	722	1'	4'	4.5 420.1	Element Survived

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
84	AC-99-4867	Coated Enriched	500	680	550	130	70.8	4920	3130	667	1'	5'	5.0 425.1	Element Survived
85	AC-99-05079	Coated Enriched	500	600	550	50	70.8	4950	3030	690	1'	25"	30.5 455.6	Element broke in three places
86	AC-09-4727	Coated Unfueled	176(H _e)	580(H _e)	550(H _e)	30	0	4420	2100	155	45"	10'	0.9 456.5T	H _e Test to check heat exchanger welds
87	AC-99-05077	Coated Unfueled	500	580	550	30	0	4490	2580	456	45"	10'	32.0 488.5T	Element Survived
88	AC-99-7919	Coated Unriched	500	620	550	70	41.6	4460	---	466	45"	5'	1.5 490.0T	Element Survived
89	AC-99-5205	Coated Enriched	500	650	550	100	41.6	4650	3120	531	45"	5'	3.5 493.5T	Element Survived
90	AC-99-5171	Coated Enriched	500	670	550	120	41.6	4740	3400	574	1'	5'	4.5 498.0T	Element Survived
91	AC-99-4866	Coated Enriched	500	650	550	100	41.6	4900	3540	616	1'	3'15"	45.5 543.5T	Element failed at hot end
92	AC-09-8290	Coated Unfueled	500	650	550	100	41.6	4650	3450	600	50"	3'10"	4.5 545.0T	Element failed at four places
93	AC-99-05166	Coated Enriched	500	640	550	90	41.6	4460	3200	530	55"	5'	7.0 555.0T	Element Survived
94	AC-99-07922	Coated Enriched	500	640	550	90	0	4790	3400	588	1'5"	2'15"	17.5 572.5T	Element Failed
95	AC-99-08293	Coated Unfueled	500	650	550	100	41.6	4460	3380	551	1'	2'30"	1.0 573.5T	Element Survived
96	AC-99-05243	Coated Enriched	500	660	550	110	41.6	4510	3540	578	1'	5'	3.5 577.0T	Element Survived
97	AC-99-05334	Coated Enriched	500	650	550	100	41.6	4510	3720	641	1'	4'	5.0 582.0T	Element Survived

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Run	No. Element	Description	H ₂ Flow (SCFM)	H ₂ Inlet (PSIG)	H ₂ Outlet (PSIG)	Δ P (PSIG)	H _e Flow (SCFM)	T Element (°R)	T Gas (°R)	(KW)	Time to Power	Time at Power	ΔW (Grams)	Comments
98	AC-99-0 5199	Coated Enriched	500	670	560	110	41.6	4820	3700	720	1'	2'-40"	17.5 599.5T	Element Failed
99	AC-99-0 4899	Coated Enriched	500	675	560	115	71	4460	3180	562	1'	5'	2.0 601.5T	Element Survived
100	AC-99-0 5196	Coated Enriched	500	675	560	115	71	4490	3140	576	1'	5'	2.0 603.5T	Element Survived

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HYDROGEN CORROSION FACILITY

Figure 1. Layout of Hydrogen Corrosion Facility

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Figure 2. High Temperature Test Cell

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Figure 3. Control Room

Figure 4. Single Element Hydrogen Corrosion Furnace

Figure 5. Transition Section and Connector

SECTION B-B

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Figure 9. Schematic of Electrical Control System

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Figure 10. Schematic of Electrical Power

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Figure 11. Original A-2 Chucks

Figure 12. Tapered Insert Chuck

Figure 13. Ball and Socket Chuck

Closed Position

Open Position

Disassembled

Figure 14. A-2 Expansion Chuck

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Figure 15. Calibration of Optical Pyrometer

Figure 16. Weight Loss Spectrum for Coated, Enriched Elements

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Figure 17. Element Temperature Profile