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SINGLE CLUSTER CORROSION TEST SUMMARY
AUGUST 1965 TO MARCH 1966
(Title Unclassified)

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AUGUST 1965 TO MARCH 1966
(Title Unclassified)

by

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Reactor Design - Specification and procurement of reactor grade hardware; design of special test hardware.

Reactor Analysis - Specification of orifices and prediction of other test parameters.

Materials - Metallographic inspection of support components.

Engineering Mechanics - Instrumentation of tie rods and preparation of support blocks for test.

Astrographics - Photographic coverage of all cluster tests.

Program Control - Procurement of reactor grade hardware.

Machine Shop - Fabrication of support hardware.

Reactor Assembly - Special cluster assembly tooling.

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ABSTRACT

This report is a progress report which presents accomplishments on the HHT-4 Cluster Corrosion Test from September 1965 to March 1966. The development of hardware, techniques, and procedures to upgrade the state-of-the-art of high temperature corrosion testing of complete clusters is discussed. In addition, testing of support block and components designs in support of NRX-A4 and NRX-A5 designs using the cluster test is reviewed.

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I. INTRODUCTION

A. BACKGROUND

The concept of testing full clusters at reactor temperatures with hot, flowing hydrogen gas was first advanced in early 1963. It was generally felt that such a component test would provide a closer approximation of reactor operating conditions than could be attained in smaller component tests. For example, the effects of temperature levels, of tie rod coolant flows, and of flow through the support block could be observed more realistically. However, it was also admitted during these conceptual stages of the test that many technological problems would have to be overcome.

Among these problems was the design and installation of a furnace, power supply, and delivery system capable of handling three megawatts of power at about 35,000 amperes. In addition, the fixturing and chucking arrangement to provide adequate transmission of this tremendous current flux to the fuel elements had to be designed. And because temperatures in the area of 5000°R were to be attained, problems of insulation, thermal expansion, and adequate cooling of furnace components remained to be solved. Finally, a technique of measuring high temperatures in all parts of the test piece for proper furnace control had to be perfected.

The design and installation of the flow system, furnace, power supply, and cluster fixturing proceeded during the ensuing months and resulted in the first full-cluster test on November 24, 1964. The results of this test as well as a description of the furnace installations and power supply were previously reported.¹ The test was basically a system check-out as were the following two which were made after the power capacity had been substantially increased.

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At about the same time the first actual test requirements for the cluster test program were being defined. These included a qualification test on the exit gas thermocouple proposed for the NRX-A4 reactor as well as a study of the support block cracking phenomenon observed in the NRX-A3 reactor test in Nevada. A previous reporting of the results of these early tests indicated that many operational difficulties in cluster testing still had to be overcome.² Arcing at the cold end and hot end chucks frequently caused pre-mature cluster failure due to element breakage. Severe bowing of elements occurred because of thermal expansion and inadequate lateral and axial support.

In spite of the fact that new problem areas were discovered, these tests solved most of the basic problems of high temperature, high current testing and pointed the way to advancements in the technique. For example, a new hot end chuck was developed, an improved method for insulating the central element and tie rod was used, a lateral support system was designed, adequate techniques for power, flow, and temperature control were established, and a cluster pre-loading technique was developed.

At this point, interest in support block design was gathering momentum because the post-test examination of NRX-A3 support blocks indicated that a major portion of them had been cracked along the counterbore radius. All of the cluster tests performed since then - some of which are reported herein - were directed toward the understanding of the cracking phenomenon and to its obviation in future designs.

B. OBJECTIVES

The objectives of the HHT-4 cluster corrosion test are two-fold:

- (1) To develop an adequate technique for testing full NERVA clusters at conditions of flow, temperature, and pressure which approximate the reactor operating conditions.

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- (2) Using this technique, to test a series of support block designs for endurance at reactor conditions to provide data for new block designs as well as to provide endurance bench marks on which to specify test conditions for NRX-A4, NRX-A5, XE-1, NRX-A6, and future reactor tests.

C. STATUS OF PROGRAM

1. Support Block Tests

The following endurance tests were established as part of the HHT-4 single cluster test program in support of the design of support blocks and related cluster components for NRX-A4 and NRX-A5 reactor tests:

<u>Description</u>	<u>HHT-4 Test Number</u>
NRX-A3 Support Block, Uncracked	HHT-4-7
NRX-A3 Support Block, Pre-Cracked	HHT-4-8
Post-Test NRX-A3 Support Block	HHT-4-9
NRX-A4 Support Block, Pre-Cracked	HHT-4-11
NRX-A5 Support Block, Uncracked	HHT-4-10
NRX-A5 Support Block, Pre-Cracked	HHT-4-12
NRX-A5 Exit Gas Thermocouple Assembly	HHT-4-11, 13
NRX-A5 Skirtless Block	HHT-4-14, 15, 16, 17

Nominal forty minute tests were prescribed for all tests. As of March 28, 1966, tests HHT-4-7, 8, 9, 10, 11, 14, and 15 were completed. Tests HHT-4-12 and 13 were tested for approximately one fourth and two thirds of the total required test time respectively and further testing of these configurations was in progress. Tests HHT-4-16 and 17 were terminated as a result of element breakage during the start-up power ramps. Further testing of these and other NRX-A5, NRX-A6, and XE-1 configurations was postponed to

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permit modification of test hardware wherever necessary to eliminate element breakage and other causes of premature test termination.

2. Test Development

Although there are still numerous technical problem in hardware design and test operation which must be solved, considerable progress has been made in the development of the cluster corrosion test as a consistent, reliable, and efficient method of testing reactor components. Prescribed test durations of twenty minutes have been attained repeatedly with normal shut downs. Longer tests can be expected with the use of back-coated elements to reduce the interelement corrosion downstream of the hot end chuck, which now limits the test duration. Element bowing with resulting arcing and breaking has been reduced substantially by the introduction of an improved orificing technique and a partial redesign of chucks and lateral supports to relieve stresses caused by thermal expansions of cluster components. Arcing between the upper and lower chucks and the fuel elements has been minimized by the use of near optimum gaps between elements and chucks and by the use of pyrofoil under the upper chuck finger grips. In addition, the down-time between tests has been substantially reduced with the adoption of standardized assembly procedures, hardware designs, and inventory controls. Furthermore, furnace control has been improved by the addition of additional temperature sensors, the further optimization of pyrometry, and by the upgrading of test data acquisition and process controls.

In spite of these advances, complex technical problems such as the attainment of nominal thermal transients on start-up remain to be solved. Current efforts to upgrade the tests are described in Section II of this report.

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II. TEST DEVELOPMENT

Aside from the testing of support block designs, the cluster test has the objective of developing reliable techniques for conducting these tests. The accomplishment of the latter objective is a continuing effort which reaches plateaus but never reaches a limit. Rather, the test is being continually up-graded as more experience in its operation becomes available. The test procedures, facility equipment and controls, and cluster configurations which were employed during the tests reported in Section III are described below with particular emphasis on important modifications in equipment or techniques developed during the test series. As a result of these tests, many new test hardware designs are evolving. These will be indicated wherever appropriate.

A. TEST FACILITY

1. Flow System

A simplified schematic of the hydrogen and helium flow loops and control components is shown in Figure 1. This system is designed to bring hydrogen gas at ambient temperature to the inlet of the cluster at a prescribed, controlled pressure and flow rate and to maintain an inert helium atmosphere around the cluster to protect the graphite support hardware and furnace shielding from corrosion damage. In addition, the system cools and filters the hot effluent gases prior to flaring to prevent contamination of the test site with fuel particles.

The hydrogen is supplied from one to four tube trailers at 2400 psia, each of which contain about 115,000 SCF of gas. Outlet pressures and flow rates are controlled automatically by pneumatically operated piston and diaphragm control valves at the inlet and outlet of the furnace through a pneumatic control loop consisting of pressure transmitters, differential pressure

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Figure 1
 Simplified Flow Schematic

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transmitters (across the orifice flow meter), and proportional-plus-reset pneumatic controllers. The pressure drop across the cluster is controlled by the size of the jet orifices used in the inlet of the element flow channels.

Helium flow to the furnace body is likewise controlled through a system of pneumatic controls to maintain a prescribed differential pressure above the hydrogen inlet pressure. This prevents gross hydrogen flows through the furnace body which would rapidly corrode the radiation shields and graphite support hardware in the furnace as well as the uncoated outer surfaces of the fuel elements. To help maintain this differential pressure in favor of the helium, a gas seal is used in the inlet end of the cluster assembly. If the gas seal between the helium atmosphere and the hydrogen inlet is effective, two operational problems result: First, the stagnant helium becomes heated by the hot fuel cluster and transfers this heat to the surrounding furnace parts. Secondly, the increasing helium temperature is accompanied by an increase in helium pressure, which if allowed to build to a high enough level, could equal the coolant pressure drop across the furnace and unseat the cluster. To solve these problems, a controlled helium atmosphere bleed was installed to continuously drain the heated helium from the furnace. This modification was made by replacing a shutoff valve in the helium atmosphere exhaust line with a panel operated flow control valve. This system has provided close control of the helium atmosphere pressure.

The clusters are tested in a water jacketed pressure vessel shown in Figure 2. Power leads from the main electrical bus bar are connected to water cooled electrodes at both ends of the furnace body. Four water cooled view ports permit continuous monitoring of surface temperatures along the length of the cluster during testing. To maintain the stainless steel vessel below

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Figure 2
Cluster Corrosion Furnace

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design temperature limits water is circulated through the jacket around the periphery. In addition, a series of radiation shields are used. Starting near the cluster there are five concentric graphite shields separated by 3/8 inch annular gaps. Near the furnace wall an aluminum oxide insulator is employed. Access to the furnace is achieved through breech locks at either end, and furnace maintenance and repair is facilitated through a trunnion mount which provides for complete rotation of the vessel.

The heat exchanger indicated on Figure 1 removes the major portion of the heat added to the cluster hydrogen flow in the furnace. This heat exchanger is of the double pipe variety and utilizes ambient temperature water in either a parallel or a counter flow arrangement. It is capable of removing 2850 BTU/sec from the gas stream at normal cluster flow rates.

A persistent problem in the cluster corrosion test system has been an excessively high temperature of the heat exchanger exit gas. This high temperature gas resulted in thermal expansion of the test loop components and caused hydrogen to leak from various fittings in the system. These leaks often forced the termination of the test before the scheduled test duration could be met. Two approaches to the problem have resulted in a decrease in exit gas temperature of 200°F. The first approach consisted of switching cooling water connections to change the cooling mode from parallel flow to counter flow. This modification resulted in a drop in gas temperature from 600°F to 500°F. The second approach consisted of inserting coils of molybdenum wire into the heat exchanger tubes to break up the gas film at the tube wall. This effected another drop in exit gas temperature, from 500°F to 400°F. Since completing the two modifications, no detectable hydrogen gas leaks have been observed during the cluster corrosion tests even during tests lasting 20 to 25 minutes at full power.

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The transition between the furnace and heat exchanger is made through a jacketed elbow. The inside of the transition section is protected from the impingement of hot cluster effluent by a graphite block insert. This insert is drilled at one point to permit the monitoring of support block surface temperature through a cooled view port on the bottom of the transition elbow.

From the heat exchanger, the gases are fed through a micrometallic pressure filter to the vent stack where they are burned. The filter is examined periodically and changed when contamination reaches specified limits.

2. Power Supply

The facility power supply is graphically illustrated in Figure 3. The capacity of this power supply is 2.8 megawatts d. c. and is sufficient to heat a fuel cluster to nominal reactor temperature levels at reduced coolant flow rates of approximately 35 to 50 percent of design flow. The general operation of the power supply is as follows: Twenty-five thousand (25,000) volts a. c. are fed to the WANL hydrogen corrosion test site by the West Penn Power Company as shown in the block diagram in Figure 3. This power is 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 goes 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 function as a main contactor as well as overcurrent protection. From the switchgear the power goes to a 1600 KVA induction regulator which either bucks or boosts the 4.16 KV supply voltage. The output of the induction regulator, which can be varied continuously from 480 to 7840 volts, is fed to the primary windings of two rectifier transformers. Each transformer has two parallel double eye secondary

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Figure 3
Electrical Power Schematic

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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 is then fed to the 35,000 ampere water cooled bus leading to the test cell. 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.

3. Instrumentation

The dynamic recording of process variables such as temperatures, pressures, flow rates, strain, and axial displacement is accomplished through several different recording modes. These are:

- Recording oscillograph.
- Potentiometric millivolt recorders.
- Pneumatic recorders.

A discussion of the effectiveness of the data acquisition is presented in Section III.

At present pyrometric measurement of surface temperatures on the support block and elements is not continuous. Observations are made by test personnel and recorded manually at specified intervals during the test. The original optical system for reading fuel cluster temperatures consisted of a series of tank prisms arranged to transmit the thermal radiation from the cluster to a point where it could be observed with a disappearing filament pyrometer. A problem with this system is that the prisms absorb significant amounts of the radiation and therefore require periodic calibration. These prisms are gradually being replaced by front surface mirrors, which eliminate any

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significant absorption losses and greatly reduce the possibility of erroneous pyrometer readings. In addition, continuous indicating and recording pyrometers are being installed to provide dynamic monitoring of cluster temperatures.

B. TEST PROCEDURES

Following cluster assembly, a typical cluster corrosion test is performed as follows: The cluster is 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 and connection of instrumentation.

After the cluster is loaded and the furnace closed, the test loop gas system is evacuated, pressurized with helium, and checked for gas leaks. At the same time, the water cooling system is started, adjusted for proper coolant distribution, and checked for leaks. The electrical power supply is energized to check the cluster for continuity.

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

1. Purge system with helium.
2. Introduce hydrogen to the system.
3. Bring hydrogen up to the desired pressure and flow rate.
4. Apply electrical power in a series of step functions until desired power level is reached. (The step function generally consists of 10 volt steps applied ten seconds apart.)
5. Maintain all parameters of hydrogen pressure, hydrogen flow rate, and electrical power input constant during the run.

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6. After specified power duration is complete, decrease power in a series of step functions of approximately 10 volts in ten seconds.
7. Continue hydrogen flow for ten minutes to cool furnace.
8. Purge with helium.
9. Shut off all systems.

The following parameters are used to provide prime indication of an ensuing test failure as by element breakage, arcing, or overheating which requires test termination:

Tie rod exit gas temperature.
Tie rod strain.
Current (deviations caused by arcing).
Visual and pyrometric observation of the furnace.
Helium to hydrogen differential pressure.
Furnace body or electrode temperature.

C. CLUSTER ASSEMBLY

1. Test Configuration

The cluster configuration shown in Figures 4, 5, and 6 is the one generally employed in this test series. The individual component designs and assembly evolved from experience gained in the first six cluster tests^{1, 2} and in the corrosion testing of single elements.³ Some modifications and upgrading of designs were also based on results obtained during the tests reported herein.

The assembly consists of a normal NRX-A cluster, including six fueled elements, support block and related parts, and tie rod and accessories. The basic cluster design is modified in the area of the cluster inlet and center element to be compatible with special test requirements and

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Figure 4

HHT-4 Single Cluster Corrosion Test Assembly

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Figure 5

Component Parts Layout for a Typical Cluster Assembly

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Figure 6
Typical Cluster Assembly

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the electrical considerations not present in a reactor. In addition, special support hardware is used to bring current to and from the fuel elements for power generation, to hold the cluster in the furnace, to provide adequate loading of the support block and tie rod, and to provide the radial support normally present in a reactor from adjacent clusters.

The cluster inlet design is influenced by the requirement for simulated reactor full power loadings of 500 lbf on the support system. This loading cannot be attained in this test hydraulically because of the reduced flow level and pressure drop when compared with the reactor. A spring loaded mechanism is employed to place the tie rod in tension. The load is transmitted by reaction to the support block and fuel elements through a modified cluster plate arrangement which is heavier than normal to transmit the load uniformly over the inlet ends of the elements.

The fact that the heavy orifice plate must bear directly on the top surfaces of the fuel elements presents a problem in orificing the flow channels. The normal orificing technique is not adequate in that the plate to orifice contact pressure would be too great and would result in element breakage around the flow channels. (In a reactor the pressure loading is transmitted across the plane at the top surface of the elements; the orifice plate to orifice contact pressure is only that caused by the cluster pre-load spring.) To solve this problem, the normal orifices were modified by welding a one inch length of .090 inch O.D. tubing to the lower ends to form an extension of the orifice outlet. This extension is inserted through the top of the large plate and 1/4 inch into the flow channel. Orifice sealant is applied to the bottom of the plate and under the orifice flanges at the top of the plate to prevent gas leakage into the flow channels and confine the flow to that through the orifices.

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Unlike the clusters in a reactor, the power generation takes place in the fuel elements by resistance heating. To avoid power generation in the center element, which would quickly overheat and melt the tube liner and tie rod, the central element is electrically insulated from the fuel elements. This is accomplished in the cooler portion of the cluster where temperatures are below 3500°R by beryllium oxide and boron nitride insulators which are machined to the outer configuration of the center element. In the high temperature portions, below the 18 inch station, the insulation is accomplished by machining the hexagonal central element to a cylindrical shape to provide a gap between the fuel elements and the center element. The hexagonal shape is retained near the hot end to maintain the concentricity of the center element and fuel elements.

The tie rod is at ground potential at the hot end where it contacts the support block. At the cold end it is insulated from the cluster by a boron nitride insulator which fits between the centering bushing and the split bushing.

Electrical contact between the fuel and the electrodes is made through chucks at each end of the cluster. The hot end chuck is a one-piece cylinder which is broached to the cluster configuration on the inner surface. As the temperature of the elements increases, they expand into the chuck to form a tight gas seal and good electrical contact. At the cold end, where the radial expansion of the cluster is relatively small, the contact pressure is mechanically achieved through a split finger chuck. The fingers, machined to the cluster configuration, are forced against the cluster by wedges loaded with a retaining nut. Pyrographite foil is used underneath the chuck to prevent arcing due to irregularities in the two contacting surfaces.

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A series of five lateral support rings are approximately equally spaced between the two chucks to provide radial strength to the cluster. These rings are comprised of split rings machined to the cluster cross section which are forced into place around the cluster by split wedges and retaining nuts within a solid clamp ring. The outer surface is held away from the furnace shields by boron nitride spacers which also insulate the cluster from the shields. Molybdenum struts maintain the spacing between the lateral supports.

Retention of the cluster in the furnace body is accomplished with an insulated support plate which rests on the furnace electrode flange. The flange of the pre-load spring housing at the cluster inlet rests on the lower portion of this support plate. Secondary retention in the event of tie rod failure takes place on the shoulders of the hot and cold end chucks.

2. Developmental Areas

One of the aspects of cluster testing that makes it orders of magnitudes more complex than the testing of single elements or other smaller test models is the interdependence of components. A failure in one small part can immediately overstress other adjacent parts. For example, if one fuel element fails by cracking, the overall electrical resistance of the cluster increases and adjacent elements become hotter while the broken element cools. The non-uniform heating can overstress adjacent elements until they crack, and the failure rapidly progresses until complete cluster failure results. As a further example, if the cold end chuck binds in the furnace electrode retainer and fails to move axially as the cluster grows thermally, the load on the elements could increase beyond the critical bending load and failure would result.

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A second aspect of the test which presents complex technical problems is the fact that in several areas mutually exclusive design parameters must be met. Thus in the cold and hot end chuck, it is necessary to provide for good electrical contact between all parts, maintain a positive gas seal to prevent hydrogen corrosion of chuck parts, provide for axial and radial thermal expansion, and provide adequate heat transmission to the water cooled electrode to maintain the chucks at a temperature within safe operating limits. To provide for large expansions and facilitate axial movement, large gaps between components of the chucks are required. Small gaps are, however, necessary for gas sealing, heat transfer and electrical contact. The optimum design must be a trade off between these demands.

The failure of cluster tests, either during start-up or during the full power hold, is the direct result of the fact that in many respects the above considerations are not being satisfied completely. The current design provides an adequate test configuration if all of the inter-related design parameters are met. But the fact that failures often occur with cluster configurations that also are completely successful suggests that the design of the configuration is marginal. A more ideal approach is to establish a cluster design configuration which has a margin of safety and in which each of the parameters can vary over broader ranges without, in themselves, causing a gross failure.

Under this design philosophy, the current upgrading of hardware is being undertaken in the following areas:

- a. Design of a "floating" upper electrode to permit unrestrained axial and limited radial movement of the cluster at the inlet end.
- b. Design of a hydrogen inlet plenum to assure a measured hydrogen flow to the jet orifices and to separate hydrogen flow from helium

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flow in the furnace body thus eliminating corrosion in the furnace body and on the outer surfaces of the elements.

- c. Design of a more reliable lateral support system to assure adequate radial support and to permit studies of interelement corrosion when desired.
- d. Re-design of the lower chuck and diffuser to provide better simulation of reactor environment around the support block.
- e. Design of a hot end chuck to allow for free radial expansion while satisfying the requirements for good electrical contact and gas sealing.

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III. SUPPORT BLOCK TESTING

A. TEST CONFIGURATIONS

The tests in this series were conducted both to study the causes of support block cracking and the effects of the cracks on the endurance capability of the block and other support hardware as well as to evaluate designs which were advanced to alleviate the cracking phenomenon. Thus the first test in this group, HHT-4-7, was an attempt to simulate the cracking observed along the counterbore radius of NRX-A3 blocks. Tests HHT-4-8, 9, and 11 were to evaluate the effect of the pre-existing crack on other support hardware and on the expected lifetime of the cluster support system at full-power reactor conditions. To evaluate new designs intended to reduce cracking or alleviate its effects, test HHT-4-10 was conducted and tests HHT-4-12 and 13 were in progress. The skirtless block was evaluated in tests HHT-4-14 and 15. Two candidate exit gas thermocouple designs were evaluated as parts of tests HHT-4-11 and 13.

Table I is a summary of the current test series which provides general descriptive notes on the test configurations, test dates, and HHT-4 test numbers. Note that in most cases more than one test cycle is specified. This reflects the fact that test cycles of a maximum of twenty minutes were prescribed for this series for two reasons: to include the influence of repeated start-up and shut-down transients in the evaluation of support blocks and to minimize test failures because of element corrosion. The latter phenomenon was observed to occur in the uncoated area above the tips of the elements from the "back wash" effect of the hydrogen around the cluster downstream of the hot end chuck. Employing elements back-coated two inches from the tips should increase the possible duration of tests substantially. Although the back-coated NRX-A5 grade elements were employed in tests HHT-4-16 and 17, failures on start-up made long term evaluations of the elements impossible.

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Table I
 HHT-4 Test Summary

Test Number	Test Configuration	Date of Test
HHT-4-7	NRX-A3 block, uncracked; "as-built" NRX-A3 components.	9-2-65
HHT-4-8a	Pre-cracked NRX-A3 block and "as-built" NRX-A3 components.	9-22-65
HHT-4-8b	Cycle 2 of above.	10-8-65
HHT-4-9a	Post-test NRX-A3 block from NRDS; "as-built" NRX-A3 components.	11-8-65
HHT-4-9b	Cycle 2 of above.	11-17-65
HHT-4-9c	Cycle 3 of above.	12-6-65
HHT-4-10a	NRX-A5 design block, ten 10-mil pyrofoil washers, 90-mil radius x .257 inch thick coated pyrographite support washer.	1-5-66
HHT-4-10b	Cycle 2 of above.	1-14-66
HHT-4-10c	Cycle 3 of above.	1-20-66
HHT-4-11a	NRX-A4 design block, pre-cracked, 70-mil radius x .317 inch thick coated pyrographite support washer, hollow tie rod and NRX-A5 exit gas thermocouple assembly, coated pyrographite insulating cup (extended).	1-26-66
HHT-4-12a	NRX-A5 design block, pre-cracked, ten 10-mil pyrofoil washers, 90-mil radius x .257 inch thick coated ATJ support washer.	2-3-66
HHT-4-13a	NRX-A5 design block, uncracked, ten 10-mil pyrofoil washers, 90-mil radius x .257 inch thick coated ATJ support washer, hollow tie rod and exit gas thermocouple assembly, coated pyrographite insulating cup (extended), tungsten-coated molybdenum protection cup.	2-5-66

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Table I (Continued)

Test Number	Test Configuration	Date of Test
HHT-4-13b	Cycle 2 of above.	2-11-66
HHT-4-14a	NRX-A5 skirtless block, coated ATJ support washer, coated ATJ protection cup, tie rod button thermocouple.	2-9-66
HHT-4-14b	Cycle 2 of above.	2-15-66
HHT-4-15a	Same configuration as test 14 without tie rod button thermocouple.	2-17-66
HHT-4-15b	Cycle 2 of above.	2-18-66
HHT-4-15c	Cycle 3 of above.	2-21-66
HHT-4-16a	Same configuration as test 15.	2-23-66
HHT-4-16b	Cycle 2 of above.	2-26-66
HHT-4-17a	Same configuration as test 15.	2-25-66

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Prior to test HHT-4-10, much of the hardware made available for component tests was not reactor grade. Thus, fuel elements had varying degrees of coating, graphite, or geometric deficiencies and support washers, tie rods, and other components were similarly defective. Much of the uncertainty in test results and some loss of time in test development was due to the use of the reject hardware. Therefore, all test clusters after HHT-4-9 were made from reactor grade components which had been specified for NRX-A5 requirements. In some cases, where new designs were being evaluated, the prototype parts were inspected prior to use according to NRX-A5 standards. Table II lists the part numbers of cluster components used throughout this series with exceptions noted by test number. Parts used in HHT-4-7, 8, and 9 not listed in the table were NRX-A2 and NRX-A3 design parts. Appendix B is a compilation of lot numbers and serial numbers for the particular reactor grade components used in each test.

Fuel elements were obtained from a pool of XE-1 candidate elements for all tests prior to HHT-4-16. After this test, all elements were NRX-A5 reactor grade elements. The XE-1 elements were from batches which were accepted on the basis of corrosion tests; however, complete quality inspection and acceptance was not completed. These elements were, therefore, screened and inspected in Fluid Flow Laboratory prior to use. In many cases small defects were accepted when it appeared that test objectives would not be compromised. This type of defect included chips in the inlet end, small coating chips, or geometrical variations somewhat beyond reactor tolerances. However, other features were demanded which appeared to have importance in cluster testing. These included the absence of holes or scratches in the element faces, absence of twist and bow within drawing tolerances, uniformity of length, weight (loading), and across-flats dimensions, and general uniformity of coating in the bores and on the tips.

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Table II
Reactor Grade Components Employed in Cluster Tests

Part Description	Quantity per Cluster	Part Number	Tests in Which Used
Fuel Elements	6	XE-1 Candidate NRX-A5 Grade	10 to 16 16, 17
Split Bushing	1	946 C 216 HO2	10, 12, 14, 15, 16, 17
Split Bushing	1	946 C 216 H14	11, 13
Compression Spring	1	978 D 695 HO1	All
Spring Shim	1 to 10	946 C 684 HO1	All
Tie Rod (Solid)*	1	945 C 568 HO1	10, 12, 14, 15, 16, 17
Tie Rod Assembly (Hollow)	1	978 D 580 GO2	11, 13
Tie Rod Nut	1	946 C 053 HO1	10, 12, 14, 15, 16, 17
Tie Rod Nut	1	946 C 670 HO1	11, 13
Tie Rod Pin	1	963 B 339	10, 12, 14, 15, 16, 17
Tube Liner	1	978 D 347 HO8E	All
Insulating Sleeve, Counter-sunk	1	946 C 970 HO2	All
Insulating Sleeve, Tapered	2	946 C 120 HO1	All
Insulating Sleeve, Tapered	2	946 C 121 HO1	All
Insulating Sleeve, Straight	12	946 C 969 HO1	All
Tube Liner Adapter	1	978 D 351 HO1	All
Support Cone	1	976 D 449 HO1	All but 11, 13
Insulating Washer	1	963 B 257 HO1	All
Insulating Cup	1	944 C 889 HO1C	10, 12
Insulating Cup	1	978 D 636 HO1	14, 15, 16, 17
Insulating Cup	1	978 D 575 HO1	11, 13
Support Washer, Pyro	1	946 C 687 HO2	10 ⁺ , 11

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Table II (Continued)

Part Description	Quantity per Cluster	Part Number	Tests in Which Used
Support Washer, ATJ	1	978 D 960 HO1	14, 15, 16, 17
Support Washer, ATJ	1	978 D 960 HO3D	12, 13
Protection Cup	1	978 D 959 HO1	14, 15, 16, 17
Pyrofoil Washers	10	947 C 043 HO1	10, 12, 13
Support Block	1	909 E 371 HO3	11
Support Block	1	909 E 371 HI0	10, 12, 13
Support Block	1	937 J 924 HO2	14, 15, 16, 17
Thermocouple Support Assembly	1	978 D 579 GO2	11, 13
Tungsten-Rhenium Thermo- couple	1	979 D 149 HO2	11, 13
Chromel-Alumel Thermo- couple	1	978 D 186 HO1	All after 11
Tungsten-Molybdenum Cup	1	979 D 497 HO1	13

*Button modified on test 14.

+Modified to 90 mil radius.

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B. SUMMARY OF TEST RESULTS

1. Test Parameters

Several process variables were dynamically monitored during each cluster test for the purpose of maintaining furnace control at specified test conditions. Thus cluster exit pressure and hydrogen flow rate were established at specified control points prior to the electrical power ramp. Power input was adjusted to provide temperature control in either the exit gas stream or on the support block surface on the aft face. Both tie rod exit gas temperature and tie rod strain, also monitored continuously, were used as prime indications of element cracking or other modes of failure which would warrant terminating the test cycle. Cluster pressure drops were also recorded continuously and showed, by their deviations from normal values, element cracking.

Surface temperatures along the B element of the cluster were monitored at full power or steady-state conditions through the four available viewports by pyrometer. Support block surface temperature was also measured pyrometrically at selected intervals during the full-power hold.

The helium used in the furnace body surrounding the cluster was maintained at a pressure approximately 1 to 2 psi higher than inlet hydrogen pressure to prevent excess corrosion on the surface of the cluster and in the furnace shields and chucks. This differential pressure as well as the helium flow rate and absolute pressure were also monitored continuously.

Table III summarizes the significant parameters measured during the test cycles, their estimated accuracies, and the instruments used in sensing, indicating, and recording them. Table IV is a summary of the steady-state values for these parameters at the full-power hold.

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Table III
 Significant Test Parameters

Parameter	Method of Sensing and Recording	Estimated Accuracy (% of Indicated)
Support Block Temperature	Optical Pyrometer	± 2
Element Surface Temperature	Optical Pyrometer	± 1.5
Exit Gas Diffuser Temperature	W-W/26% Re Thermocouple; Millivolt Recorder	± 1.0
Tie Rod Exit Gas Temperature	Chromel-Alumel Thermocouple (978 D 186 HO1A); Millivolt Recorder	± 1.0
Tie Rod Button Temperature	Chromel-Alumel Thermocouple (978 D 186 HO1A); Millivolt Recorder	± 1.0
Cluster Exit Gas Temperature	W-W/26% Re Thermocouple; Millivolt Recorder	± 1.0
H ₂ and He Flow Rates	Square Edged Orifice; Differential Pressure Transmitter; Pneumatic Recorder	2%
H ₂ and He Pressures	Pneumatic Pressure Transmitter and Recorder	1.5%
Cluster Pressure Drop and H ₂ /He Differential Pressure	Pneumatic Differential Pressure Transmitters and Recorders	1.5%
Tie Rod Strain	Four-arm Bridge Resistance Strain Gage; Recording Oscillograph	2%
Current	Millivolt Recorder	± 1.0
Voltage	Millivolt Recorder	± 1.0
Coolant Water Temperature	Chromel-Alumel Thermocouples, Millivolt Recorders	± 1.0

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Table IV
Test Conditions and Results

VARIABLE	HHT-4 TEST NUMBER																			
	7	8a	8b	9a	9b	9c	10a	10b	10c	11a	12a	13a	13b	14a	14b	15a	15b	15c	16a	17a
Test Duration	13.0	15.0	8.0	20.0	7.3	2.0	30.0	13.0	17.0	36.0	21.0	28.0	33.0	31.0	20.0	30.0	10.0	4.7	4.1	3.2
Equivalent Time, Min., at 4150°R	7.5	5.8	5.5	17.0	1.8	0.2														
at 4283°R	6.0	4.7	4.5				22.7	5.5	9.4	36.6	13.0	20.1	19.6	20.0	10.2	14.9	4.2	2.5		
Support Block Surface Temperature, °R	4290	4330	4210	4180	(4150)	(4150)	4480	4360	4410	(4600)	(4210)	(4150)	(4300)	(4300)	(4350)	4350	3880	(4350)		
Cluster Exit Gas Temperature, °R																				
1/2 Inch From Block										4710		4290	4325							
3 Inches From Block		4000	4400					4180	4495	4660	4265	3980	4380	4170	4480	4370	4010	4470	3800	3920
Element Surface Temperature, °R																				
Station 43	3880	3710	4680				4470	4230	4420	4990	4650	4430	4960	4450	5230	5100	4330	4840		
Station 35	3740	3340	4250	3790			4190	4010	4250	4750	4300	4070	4250	4141	5070	5000	4070			
Station 16	2740	2380	3180				4280	3970	4360	4720	4110	4050	4120	4220	3800	3580				
Station 8							3220	2240	3000	2480	2250	2170		2310		2850	2400			
Exit Gas Diffuser Material Temperature, °R									3260	3760										
Tie Rod Exit Gas Temperature, °R											1635		1152		1130	1066	1066	1534	2600	2600
Tie Rod Button Material Temperature, °R														1105	1238					
Hydrogen Flow Rate, lb/sec	0.095	0.098	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.109	0.095	0.109	0.095	0.095	0.095	0.096	0.104	0.095	0.095	0.096
Helium Flow Rate, lb/sec						0.014	0.024	0.024	0.006	0.010	0.013	0.007	0.009	0.010	0.013	0.013	0.010	0.022	0.027	0.017
Cluster Outlet Pressure, psia	560	560	560	560	560	560	565	565	565	565	565	565	565	565	565	565	565	565	565	565
Cluster Pressure Drop, psi	30	40	34	36			60	60	42	58	56	54	42	46	50	50	50	22.5	15.0	20.0
Electrical Power Input, MW	1.69	1.91	2.18	1.50	1.51	1.62	2.26	2.02	2.14	2.42	2.12	2.09	2.09	1.96	2.29	2.26	2.25	2.02	1.99	2.00
Overall Resistance, Milliohms	6.53	8.85	7.75	9.45	9.53	9.65	8.93	8.75	8.26	8.95	8.58	8.84	8.45	9.05	9.43	8.91	8.70	8.52	8.37	8.06
Current, Kiloamps	16.10	14.70	16.80	12.60	12.60	12.95	15.90	15.20	16.40	16.45	15.75	15.40	15.75	14.70	15.60	15.92	16.10	15.40	15.40	15.90
Voltage, Volts	105	130	130	119	120	125	142	133	133	147	135	136	133	133	147	142	140	131	129	127
Tie Rod Pre-Load, lbf	441	470	470	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	300	300
Maximum Tie Rod Load, lbf	674			600		685		773		904	843	723	822			783	871	870	590	561
Tie Rod Orifice Diameter, mils	50	50	50	50	50	50	32.5	35	40	50	40	70	70	45	52	52	52	52	52	52

() = Estimated From Power Input

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In some cases, pyrometric coverage of the support block was obscured by graphite dust, a movement in one or more components of the optics system, or by the molybdenum shield in the exit gas diffuser. In these tests values included in parentheses in the table were estimated from correlations of support block temperature versus power input from other tests based on the power input for the test in question.

Both the support block and element surface temperatures shown in the table include corrections for losses in the optical system and for variations in observed temperatures from true black-body temperatures because of niobium carbide emissivity. The optical corrections were determined experimentally by observing a hot tungsten filament both directly in air and through the entire optical train as the temperature of the filament was varied from 2000°R to 5000°R . The emissivity correction was determined by observing two adjacent areas on a heated fuel element one of which was coated with niobium carbide and one of which was the uncoated surface of the fuel element. Values of observed temperature were recorded for both areas as the element was heated from 2000°R to 5000°R .

The test durations shown in Table IV were times during which power was applied to the cluster. Since for part of this time the support block was below or above the desired steady-state temperature as in the case of power ramps and excursions during the power hold, it was necessary to define a parameter by which the performance of each block could be compared with that of other blocks. The equivalent time at 4150°R and 4283°R was chosen for the NRX-A3 blocks and NRX-A4, A5 blocks respectively. The equivalent time for each test was defined as the time at the specified temperature (4150°R or 4283°R) which could be expected to produce the same degree of graphite corrosion as the particular block experienced over its entire test profile.

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This calculation was based on the reaction of pure hydrogen and carbon to methane using kinetic data presented in the NRX-A5 data book.⁴ Other rate expressions could also have been used. For example, the semi-empirical relationships for mid-band corrosion and carbon diffusion through the hot end coating could also be applied to support blocks. The methane reaction was chosen for its simplicity and for the fact that gross corrosion of graphite parts in the support hardware would be most severe after coating removal by peeling or cracking. Under the latter conditions, the methane rate expression would be applicable. The details of the technique used in the equivalent time calculations are shown in Appendix A.

In a normal reactor the effects of thermal expansion of the elements and the hydraulic forces of the core pressure drop across each cluster combine to produce a load of about 500 lbf in the tie rods which is transmitted to the support block. Since the cluster tests were conducted at about 35% of reactor cluster flow rates based on power limitations and since the clusters were held fast in the hot end chucks, it was necessary to simulate this support block and tie rod load with a mechanical spring assembly. Two values for tie rod load are given in Table IV. The first is the pre-load placed on the tie rod during cluster assembly. The second or higher value is the maximum value recorded during the test cycle and is generally no different from the steady-state value. The increase in tie rod loading during the test cycle is due to the effect of cluster pressure drop during cold flow and the effect of thermal expansion during power testing.

The increase of from 200 to 400 lbf shown in Table IV are approximately the values which would be expected based on calculations of axial expansion

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of the cluster and the spring constant of the preload springs. These expansions could be from 0.3 to 0.6 inches based on the measured axial temperature profiles shown in Table IV and Figure 7 which shows typical axial temperature profiles for tests in this series.

The helium flow rates shown in Table IV were those required to maintain the furnace body at a higher pressure than the hydrogen inlet. Although some of the helium leakage occurred through the hot end chuck, through inter-element gaps, and through a furnace atmosphere bleed line, some amount also could have leaked through the cold end chuck into the cluster inlet plenum. This leakage would then be mixed with the hydrogen and proceed through the orifices to the element bores. It is estimated that such helium flow was less than three percent of the total hydrogen flow. Steps are currently being taken to eliminate this leakage entirely by enclosing the orifice plate and element inlets in a separate housing apart from the helium atmosphere.

Since the power supply limited the cluster flow rates to about 0.1 lb/sec of hydrogen, exact simulation of reactor levels in the element, tie rod annulus, and support block could not be precisely achieved. Support block material temperature and cluster exit gas pressure were reproduced while cluster pressure drop, tie rod exit gas and material temperatures, and element temperature profiles assumed values based on these control variables and the split between cluster flow and tie rod flow. This split was based on the relative sizes of the tie rod orifices in the centering bushing and the 30 and 33 mil orifices used in the element channels, Table V compares typical HHT-4 results for these variables with those calculated for the NRX-A5 reactor and illustrates the degree of simulation achieved in these tests.

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Figure 7

Typical Axial Temperature Profiles for HHT-4 Cluster Tests

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Table V
 Comparison Between Typical HHT-4 and NRX-A5
 Cluster Parameters at Full Power

Parameter	HHT-4	NRX-A5 ⁽⁴⁾
Cluster Hydrogen Flow Rate, lb/sec	0.0950	0.2677
Tie Rod Annulus Flow Rate, lb/sec	0.0096	0.0146
Cluster Pressure Drop, psi	50	125
Tie Rod Exit Gas Temperature, °R	1100	577
Cluster Exit Gas Temperature, °R	4283	4283
Station 43 Temperature, °R	4675*	4280 ⁺
Station 35 Temperature, °R	4463*	3925 ⁺
Station 16 Temperature, °R	4121*	2193 ⁺
Station 8 Temperature, °R	2547*	1441 ⁺
Support Block Temperature, °R	4283	4283
Power Input to Gas, mw	1.50	4.12
Total Power Input, mw	2.00	----
Tie Rod Diameter, Inches	0.110	0.110
Tie Rod Bushing Orifice, Inches	0.052	0.0325

*Surface

+Channel Wall

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The simulation of the environment around the support block periphery is at present somewhat uncertain. In the reactor, adjacent support blocks limit heat losses from the outer surfaces of the blocks. Therefore, thermal gradients are set up only because of the differences between the tie rod exit gas temperature and the cluster exit gas temperature. This difference exists in the HHT-4 test also; however, there is also a tendency for an additional thermal gradient on the periphery as a result of radiation to the surrounding furnace support hardware which is somewhat cooler than the support block. Gradients set up in the blocks because of these radiation losses are believed to be small, particularly when a molybdenum reflector is employed as a shroud around the block. However, their significance has not yet been firmly established.

2. Component Weight Losses

Wherever feasible, graphite components were weighed before and after each test cycle to determine the weight losses sustained. In some cases where more than one cycle was conducted, assemblies were not removed between cycles, and only an initial and final weight were measured. In still other cases, as for example the skirtless blocks, welding of components during the high temperature cycle made it impractical to obtain individual component part weights. These observations should be kept in mind in reviewing Table VI which summarizes the available weight loss data for this series of tests.

The significance of the weight loss data will be discussed in the following descriptions of individual support block endurances. However, one point of caution should be advanced here in the use of this data. The values given for "weight loss" are really "weight changes" and reflect occurrences of the following phenomena either separately or in concert:

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Table VI
 Summary of Weight Loss Data

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COMPONENT	LOSS	HHT-4 TEST NUMBER														
		7	8a	8b	9a	9b	9c	10a	10b	10c	11a	12a	13a	13b	14a	15c
Support Block, Grams		0.8	0.7	1.2	2.4	0.3	0.5			11.3	5.1	2.7		7.5 ⁺	2.6 ⁺	(3.7) ⁺
Percent of Initial		0.445	0.406	0.698	1.40	0.175	0.292			6.25	3.36	1.58		4.38	2.12	3.0
Support Washer, Grams							0.2			3.0	1.5			0.05 ⁺		
Percent of Initial							6.65			26.5	51.7			2.11		
Insulating Cup, Grams										0.6	3.3	0.1		1.3 ⁺	0.18 ⁺	0.3 ⁺
Percent of Initial										21.4	55.0	3.45		21.1	6.04	10.0
Pyrofoil Washers, Grams										0.091				0.2 ⁺		
Percent of Initial										14.20				22.3		
Aft Insulating Sleeve, Grams														0.5 ⁺		
Percent of Initial														7.05		
Insulating Washer, Grams																.05 ⁺
Percent of Initial																8.33
Center Element, Grams		1.2	8.5		1.9	0.4	2.9	0.1	-2.5*	0.3	5.3	8.7			10.8 ⁺	
Percent of Initial		0.485	3.4		0.697	0.145	0.969	0.041	0.918	0.108	1.880	3.10			3.90	
Fuel Elements, Grams ^x		10.1	33.7	40.2	46.5	12.0	30.8	80.3	35.2	45.8	146.7	38.3	35.5	74.4	42.6	52.6
Percent of Initial		0.237	0.802	1.045	1.130	0.304	0.783	2.06	0.903	1.129	3.93	0.986	0.910	1.915	1.100	2.59
Protection Cup, Grams															(0.3) ⁺	
Percent of Initial															(4.83)	

() = Estimate
 * = Weight Gain by Deposition
 + = Cumulative Loss.
 x = Total for Six Elements

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- a. Graphite corrosion losses.
- b. Coating losses as a result of chipping or peeling.
- c. Deposition of carbon or other materials from upstream in other portions of the cluster.
- d. Losses of material sustained in handling the cluster components during assembly and disassembly.

The net result is that the weight loss data do not provide an accurate accounting per se of graphite corrosion losses and should not be employed without additional facts to predict such losses.

C. DISCUSSION OF INDIVIDUAL TESTS

1. HHT-4-7

Post-test examination of the NRX-A3 reactor after operating at full power hydrogen flows and temperatures for 16.5 minutes indicated that most of the support blocks had suffered cracking in the area of the counterbore radius. It was postulated that the cracks, which penetrated the inner row of flow channels, were caused by both mechanical stresses and thermal stresses. The mechanical stresses were a result of the load carrying at full power core pressure drop while the thermal stresses were probably most severe during the transient start-up when radial thermal gradients across the block are greatest.

The seventh cluster test was conducted to simulate the NRX-A3 support block cracking in an uncracked block in order to verify analytical predictions of the causes of the counterbore cracks. To do this a pre-load of 440 lbf was applied to the tie rod with the pre-load assembly and a rapid start-up power ramp was applied to simulate the NRX-A3 ramp program.

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A ramp rate of about 20 to 25 degrees Rankine per second, about one-half of the desired rate, was attained and a maximum load of 674 lbf was placed on the support system during the test.

Post-test examination of the block showed no evidence of damage externally, and sectioning revealed no crack development in the counterbore radius. Further attempts to simulate the NRX-A3 cracking phenomena in the cluster furnace were put aside for two reasons. One, the effect of cryogenic hydrogen at the cluster inlet could not be readily simulated and using ambient temperature gas reduced the thermal gradients in the block. Two, the required ramp rates were difficult to achieve with the current state of cluster hardware development since the elements, chucks, and lateral supports become overstressed by the rapid thermal expansions. Development work to provide the high ramp rate capability was in progress.

2. HHT-4-8

If in the NRX-A3 reactor many of the support block cracks occurred in the initial stages of the power test as would be the case if thermal stresses were a substantial contributing cause, then reactor life might be critically limited by support block failure. This might occur if severe corrosion took place in the area of the crack after the coating was broken to expose the graphite underneath. Since the NRX-A4 support blocks were similarly designed and, therefore, could also be expected to crack perhaps in the early stages of the test, it would be important to predict the lifetime of a cracked block at full power conditions. Endurance of a block for 40 minutes under full mechanical load, hydrogen temperature of 4150°R, and full hydrogen flow would help verify that the NRX-A4 reactor could be run for the anticipated 30 minutes at full power.

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The support block employed in this cluster test was pre-cracked by Engineering Mechanics Laboratory under cyclic temperature, with applied load. Two test cycles were completed. The prescribed test plan was completed in the first cycle with the block at power for 10 minutes. The equivalent time at 4150°R based on exhaust gas temperatures was 5.8 minutes. Figure 8 shows that no significant external corrosion, chipping, or loss of coating took place.

In the second cycle, element breakage dictated a test abort after 5.5 minutes at 4150°R . Figure 9 shows the post-test condition of the block. Several chips in the coating and graphite can be seen on the periphery. A cumulative weight loss of 1.9 grams was measured for the 11.3 minutes at 4150°R . Sectioning of the block, Figure 10, revealed the extent of sub-coating corrosion in the counterbore area. The crack in that area extended through the block to the inner circle of flow channels. Relatively large pockets of corrosion (extending from the counterbore to the flow channels in a bell shape) are apparent in the photomicrographs. The corrosion was less pronounced in the section taken through the second circle of flow channels from the counterbore as shown by Figure 11. However, the crack and the initial corrosion damage in this cross section are also apparent.

3. HHT-4-9

The use of a support block which was cracked in the laboratory by mechanical-thermal stresses would provide a good simulation of the cracking noted in NRX-A3 blocks. To employ an actual cracked NRX-A3 block would be superior because there would be a better chance of sampling a "typical" crack, the crack could be expected to have occurred in a "typical" mode,

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Figure 8

Pre-Cracked NRX-A3 Block After 5.8 Minutes at 4150°R (HHT-4-8a)

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Figure 9

Pre-Cracked NRX-A3 Block After 11.3 Minutes at 4150°R (HHT-4-8a)

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Figure 10

50X Sectional Views of Counterbore Crack and Corrosion (HHT-4-8)

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Figure 11

50X Sectional View Between Counterbore and
Second Circle of Flow Channels (HHT-4-8b)

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and any effect of the radiation environment on corrosion would be typical of other blocks in NRX-A3 and NRX-A4 reactors. Moreover, a shorter test would be required since the NRX-A3 blocks already had been subjected to full power environment for 16.5 minutes.

One of the regular NRX-A3 blocks was procured from the Nevada Test Site following post-test inspection and decontaminated to an extent that it could be handled during cluster testing. Figure 12 shows the pre-test condition of the block as received by this laboratory. The goal of this test was to log another 23.5 minutes at 4150°R and maximum hydrogen flow to add a 40 minute endurance bench mark to the data supporting prolonged testing of NRX-A4.

Three power tests were conducted on this block on November 8 and 17 and on December 6, 1965. This first cycle was terminated after 17 minutes at full power because of arcing near the hot end chuck. Post-test inspection showed little change in the support block from the pre-test condition. It lost about 1.4 percent of its initial mass primarily on the peripheral edges of the upstream and downstream faces when the coating had been chipped prior to testing. Figure 13 shows the post-test appearance of the block after a cumulative time of 33.5 minutes at full power (NRX-A3 plus HHT-4-9a).

The second cycle, HHT-4-9b, reached a steady-state block temperature of 4150°R for 1.8 minutes before arcing near the top of the furnace terminating the test. A power level and flow level identical to the first cycle was reached. After disassembly and inspection it was observed that additional material loss was sustained on the edges of the block and on the downstream face as shown in Figure 14. Inspection of the counterbore radius under a 100X microscope

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Figure 12

Post NRX-A3 Block As-Received from NRDS (HHT-4-9)

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Figure 13

Post NRX-A3 Block After 17 Minutes at 4150°R (HHT-4-9a)

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Figure 14

Post NRX-A3 Block After 19 Minutes at 4150°R (HHT-4-9b)

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indicated a continuous circumferential crack in the coating, but there was no indication of the depth of the crack or of sub-coating corrosion.

A third cycle was terminated after 0.2 minutes at power when an internal short circuit in the cluster melted the tie rod near the inlet end. The block and support hardware fell through the furnace and came to rest in the transition section between the furnace and heat exchanger. The block was chipped at numerous locations on the downstream face and periphery (Figure 15) but no obvious cracking occurred. A cumulative test time of 19 minutes in these tests produced a cumulative weight loss of 3.2 grams or 1.9 percent of the "as-received" mass of the block. The total equivalent time at 4150°R was 35.5 minutes including the NRX-A3 power test of 16.5 minutes.

The post-test sections of the block shown in Figures 16 and 17 illustrate that the block survived the NRX-A3 reactor test and the HHT-4-9 test with virtually no internal structural or corrosion damage. Some sub-coating corrosion occurred between the counterbore and the inner flow holes near the trailing edge. However, no cracks or corrosion pockets were evident in the counterbore radius area in spite of the obvious cracks through the coating in that area and in spite of the fact that a support block loading of 685 lbf was recorded during the tests.

In that this block was uncracked when received, it was not typical, as presumed, of the NRX-A3 support blocks, a major portion of which exhibited cracks in the counterbore. The endurance mark of 35.5 minutes at 4150°R was, therefore, applicable only to uncracked blocks and not to blocks cracked during start-up.

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Figure 15

Post NRX-A3 Block After Final Cycle (HHT-4-9c)

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1X
Half-Section

5X
Sub-Coating Corrosion Around Flow Channel

Figure 16

Sectional Views of the Post NRX-A3 Block
After 36 Minutes at 4150°R (HHT-4-9)

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Figure 17

50X Sectional View of the Counterbore Radius (HHT-4-9)

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4. HHT-4-10

One of the designs suggested for the alleviation of the support block cracking was the use of a stack of ten 10-mil thick pyrographite foil washers between the base of the counterbore and the support washer. Mechanical testing of this configuration under steady load and cyclic temperatures showed that some improvement in the load carrying capacity of the support system could be attained before cracking occurred.⁵ However, no experimental evidence of the endurance of the foil washers at reactor conditions was available. This test was conducted to evaluate the effects of the hydrogen atmosphere and high temperatures on the stacked-foil design when used in the NRX-A5 support geometry with NRX-A5 full power temperature profiles.

An uncracked NRX-A5 design block was employed with a 0.257 inch thick coated pyrographite support washer and ten pyrofoil washers secured from Engineering Mechanics Laboratory. These washers were of the high purity, outgassed material specified for the NRX-A5 support system. The support washer was initially of reactor grade quality but was remachined to a 90 mil seat radius on the upstream edge to match the NRX-A5 design. The coating was, therefore, removed on this radius over the entire circumference of the washer. The remaining coating on the inner and outer diameter and on both faces was intact.

Engineering Mechanics Laboratory assembled the support block, support washer, foil washers, insulating cups, and lower insulating sleeve in a loading assembly designed for this purpose. A force of 700 ± 25 lbf was used to seat the foil into the counterbore cavity resulting in a mechanical seal between the foil and the block and between the foil and the last insulating sleeve.

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Three corrosion cycles of 22.7, 5.5, and 9.4 minutes equivalent time at 4283°R were conducted using the same support hardware including the last insulating sleeve while replacing the elements and other damaged parts between cycles. Figures 18 and 19 show the block and pyrofoil washers after cycle 2 and the washer and cup after disassembly. The seal between the foil and the sleeve was loosened during the second cycle. Figures 20 through 22 show the support components after the final cycle and Figure 23 is the sectioned block after final disassembly and inspection.

The pyrofoil washers sustained a cumulative weight loss of 14 percent. Corrosion occurred on the outside diameter at the interface of the foils and the counterbore. No significant corrosion damage was observed on either bearing face, the inside diameter, or between layers. The insulating cup lost 21 percent of its initial weight through the loss of coating and through corrosion largely on the trailing edge. The loss was comparable to that of other cups used in the cluster test and did not occur in an area that would tend to reduce the mechanical stability of the support system.

The support washer incurred the most severe damage with losses amounting to 27 percent of the initial weight as modified to the NRX-A5 design. The losses were largely corrosion losses on the periphery which were believed to be a result, in part, of the removal of the coating around the radius on the upstream edge of the periphery.

The support block itself survived the test with no cracking in the counterbore radius and with a cumulative loss in weight of six percent. Most of this loss took place on the periphery at the interlock and on the trailing edge of

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Figure 18

NRX-A5 Block and Foil Washers
After 28.2 Minutes at 4283°R (HHT-4-10a, b)

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Figure 19

NRX-A5 Support Components
After 28.2 Minutes at 4283°R (HHT-4-10a, b)

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Figure 20

NRX-A5 Block and Foil Washers
After 37.6 Minutes at 4283°R (HHT-4-10c)

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Figure 21

NRX-A5 Support Components
After 37.6 Minutes at 4283°R (HHT-4-10)

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Figure 22

Cup and Washers After 37.6 Minutes at 4283°R (HHT-4-10)

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Figure 23

NRX-A5 Block Sections After Final Cycle (HHT-4-10c)

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the skirt. The section shown in Figure 23 illustrates the relatively deep pocket of corrosion which occurred in the offset opposite the identification faces of the block. Some loss of material between the counterbore and innermost flow holes is also evident. Otherwise the block was not seriously damaged.

Several axial cracks were observed on the periphery both at the indented junctions of the lobes and on the flat faces of the skirt. It is possible that thermal gradients set up between the block and the somewhat cooler (3300°R) surroundings in the furnace could account for these peripheral cracks. This situation is not present in the reactor at steady-state, except on the periphery of the core, since each block is surrounded by blocks of approximately the same average temperature. In later tests, a molybdenum shield inserted in the furnace between the block and furnace support hardware appeared to be effective in reducing heat losses, thermal gradients, and peripheral cracking of the blocks.

During each test cycle, elements broke during the full power hold shortly before the power down-ramp. As a result, hot gases impinged on the center element and overheated the tie rods. Since no tie rod exit gas temperatures were recorded, it is possible that this transient temperature excursion reached temperatures in the range of 2000 to 2500°R . No serious damage was observed except for noticeable discoloration at the tip of the tie rods. Because of the extremely short duration of these excursions - perhaps one to five seconds - the effects on graphite parts were minimal. The tie rod exit gas temperature during the steady-state portions of the test was estimated on the basis of orifice size, pressure drop, and the results of other tests to be from 1300 to 1500°R .

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5. HHT-4-11

The goal of test HHT-4-11 was to establish the adequacy of the NRX-A4 support system for 40 minutes at full power based on the assumption that cracking of the blocks on the counterbore radius could be expected to occur in the early parts of the NRX-A4 power test. An NRX-A4 block was pre-cracked in the area of the counterbore radius under load and cyclic temperatures prior to testing in the cluster furnace. The "as-built" NRX-A4 support hardware was employed with the exception of the tie rod and insulating cup. These components were the NRX-A5 candidate exit gas thermocouple assembly, hollow tie rod, and extended pyrographite insulating cup. Figure 25 shows this assembly on the completed cluster assembly and Figure 24 shows the visible crack in the support block prior to the test.

In the initial attempt to ramp the cluster to full power, a hydrogen leak in the furnace caused a power shut down at a gas temperature of about 3500°R. An equivalent time of 0.3 minutes at 4283°R was logged on the block and all components, including the thermocouple, were intact after the test. Some peeling of coating from the pyrographite insulating cup occurred as seen in Figure 26. The thermocouple recorded continuously during this short cycle.

In the second cycle, full power was attained. During this test pyrometric observation of the support block was inadequate and power control was based on the less consistent station 43 element surface temperature. The result was the attainment of exit gas temperatures substantially higher than anticipated. Gas temperatures of up to 5000°R melted the thermocouple and caused extensive erosion and corrosion of the insulating cup which lost 55 percent of its initial mass. The coated, pyrographite support washer likewise underwent a substantial loss of 52 percent of its initial mass. Figure 27 reveals the extent of the damage to these components.

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Figure 24

Pre-Cracked NRX-A4 Block Prior to Test HHT-4-11

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Figure 25

NRX-A4 Block and Exit Gas Thermocouple Assembly Prior to Test HHT-4-11

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Figure 26

Coating Damage After First Power Ramp HHT-4-11

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Figure 27

NRX-A4 Washers and Insulating Cup
After 36.6 Minutes at 4283°R (HHT-4-11)

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The total equivalent time logged on the support block referred to 4283°R was 36.6 minutes. Maximum temperature for the block based on exit gas temperatures, power input, and surrounding temperature of the diffuser was estimated to be 4850°R. Although the support block and related hardware continued to function adequately for the duration of the test in spite of its pre-cracked condition, the post-test inspection revealed deep pockets of corrosion in the area of the counterbore crack and a weight loss of 3.4 percent. Except in the area of the counterbore crack, the block was not seriously damaged, the peripheral cracks and corrosion being less extensive than in the previous test of the NRX-A5 block due in part to the use of a molybdenum reflector to reduce thermal gradients in the block. Figure 28 shows the enlargement of the counterbore crack after the test while Figure 29 shows through sectional views the toroidal corrosion pocket which extended nearly 360 degrees around the counterbore seat.

Prior to melting, the thermocouple operated for three minutes with indicated temperatures within 100°R of a second tungsten-rhenium thermocouple downstream. Figure 30 is the test record of the millivolt output of the tungsten-tungsten/26% rhenium thermocouple during the two power cycle up to the failure. The extent of damage to the tie rod and thermocouple assemblies is shown by Figures 31 and 32. Except for the melting of the thermocouple in the hot gas stream, no severe damage to the tie rod cone or thermocouple support occurred. As in the previous test, no tie rod exit gas temperatures were recorded to establish the state of the environment on the inside of the support cone.

Metallographic analysis of the support components and thermocouple are in progress and results will be reported elsewhere.

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Figure 28

NRX-A4 Block Counterbore Crack
After 36.6 Minutes at 4283°R (HHT-4-11)

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Figure 29

Pre-Cracked NRX-A4 Block Sections After Test HHT-4-11

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Figure 30

Exit Gas Thermocouple Output Record HHT-4-11

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Figure 31

Pre-Cracked NRX-A4 Block and Exit Gas Thermocouple After Test HHT-4-11

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Figure 32

Thermocouple, Tie Rod Cone, and
Support Components After Test HHT-4-11

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5. HHT-4-12

In order to predict the endurance capability of the NRX-A5 reactor under the most severe conditions which might normally be expected, an NRX-A5 pre-cracked block was obtained from Engineering Mechanics Laboratory for this test. Other reactor grade hardware of the "as-built" NRX-A5 design was employed, including the 90 mil radius, coated ATJ support washer and the pyrofoil washers. The foil washers, sleeve, and support washer were installed and loaded by Engineering Mechanics Laboratory.

In the first cycle of the test thirteen minutes at 4283°R were logged with normal flow, pressures, and power input, and with a tie rod exit gas temperature of 1635°R . The test was terminated as a result of an arcing induced failure of elements near the cold end chuck. Some molten debris and soot were deposited on the support block and tie rod button. Cracks, coating chipping, and corrosion were observed on the edge of the upstream face. The damage was probably initiated by the nonuniform loading of the block by the differential expansion of adjacent elements. Two small chips also occurred on the trailing edge of the block. Except for loss of coating on the outside of the insulating cup, the foil, cup, and support washer were not severely damaged. Figures 33, 34, and 35 show the post-test condition of these components. Testing of the block through additional power cycles is in progress.

6. HHT-4-13

The first test of the proposed NRX-A5 exit gas thermocouple assembly was considered inadequate for two reasons. One, the use of a cracked NRX-A4 block without foil washers provided a flow of hot gases over the insulating cup which resulted in an unduly severe environment around the thermocouple

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Figure 33

Pre-Cracked NRX-A5 Block
After 13 Minutes at 4283°R (HHT-4-12a)

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Figure 34

Pre-Cracked NRX-A5 Block and Foil Washers
After 13 Minutes at 4283°R (HHT-4-12a)

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Figure 35

ATJ Support Washer and Insulating Cup
After 13 Minutes at 4283°R (HHT-4-12a)

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system. And two, the temperature excursion experienced during that test was at least 500°R higher than the design point for the thermocouple. Test HHT-4-13 was conducted as a special thermocouple assembly evaluation test. An uncracked NRX-A5 block was used with the foil washers, ATJ support washer, and extended pyrographite insulating cup. In addition, a tungsten-coated molybdenum protection cup was inserted as a liner for the insulating cup. This protection cup was held in place by the support cone. The foil washers, sleeve, and ATJ support washer as well as the thermocouple and support were installed by Reactor Assembly using the same loading tools designed for the assembly of NRX-A5 clusters.

Two cycles of approximately 20 minutes each were successfully completed at full power temperatures near 4283°R . Both the thermocouple assembly and the support block assembly withstood the high temperatures with relatively minor damage. Some blistering of the thermocouple sheath and support occurred, however, it was not apparent whether the surface had started to melt or whether another material had been deposited there. The coating on the insulating cup was almost entirely gone after the 20 minute cycle and the cup was corroded on the outside especially near the trailing edge. The foil washers, support washer, tie rod cone, insulating sleeve, and protection cup were essentially intact. Figures 36 and 37 show the effects of the 20 minute power test on these components.

With the exception of some "noise" on the initial power ramp, the output of the thermocouple was smooth and continuous throughout the test and responded quickly to changes in power input to the cluster. The agreement between this exit gas thermocouple and a second thermocouple downstream was within 300°R for the indicated temperatures. There were no corrections

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Figure 36

NRX-A5 Block and Exit Gas Thermocouple
After 20 Minutes at 4283°R (HHT-4-13a)

Figure 37

Exit Gas Thermocouple and Tie Rod Cone
After 20 Minutes at 4283°R (HHT-4-13a)

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made in either indicated temperature for radiation and conduction losses or for the effect of tie rod coolant flow. Correcting the downstream reading from a mixed mean temperature to a cluster exit gas temperature by subtracting the effect of tie rod coolant flow would result in agreement between the two thermocouples to within 50°R . Figure 38 is a portion of the test record for this cycle.

During the second 20 minute cycle the thermocouple operated adequately during the power ramp and for about 5.5 minutes near full power. At that point the output decreased sharply from 36.5 millivolts to 25 millivolts and remained steady for an additional 4.5 minutes. A second decrease to 18 millivolts held for about one minute before the output decreased to zero, indicating an open circuit. Figure 39, the test record for this portion of the cycle, illustrates this behavior. The thermocouple is currently being x-rayed and sectioned to determine the mode and cause of this failure and data from these tests will be reported when available.

The external appearances of the thermocouple sheath, support, tie rod cone, and protection cup did not change appreciably from those observed after the first cycle. However, the insulating cup underwent severe corrosion on the outside diameter losing about 21 percent of its initial weight. The block was structurally intact except for corrosion on the trailing edge of the skirt amounting to a weight loss of 8 percent. The foil washers were corroded on the periphery (as in previous tests) and lost 22 percent of their initial weight. Figures 40 through 42 show several views of the support components and thermocouple after 40 minutes at 4283°R .

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Figure 38

Exit Gas Thermocouple Output Record (HHT-4-13a)

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Figure 39

Exit Gas Thermocouple Output Record (HHT-4-13b)

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Figure 40

NRX-A5 Block and Exit Gas Thermocouple
After 40 Minutes at 4283°R (HHT-4-13b)

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Figure 41

Thermocouple Assembly and Cups
After 40 Minutes at 4283°R (HHT-4-13b)

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Figure 42

Insulating Cup After 40 Minutes at 4283°R (HHT-4-13b)

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7. HHT-4-14

One of the proposed solutions to the counterbore cracking problems was the removal of the lower portion of the hexagonal skirt on the NRX-A5 support block design to form the "skirtless" block. Test HHT-4-14 was the first of several tests to evaluate the endurance and structural integrity of this support system under simulated NRX-A5 conditions. These tests employed reactor grade components identical to those used in the skirtless block experiments included in the NRX-A5 reactor. One exception to this configuration was the specially instrumented tie rod.

Since the skirtless block design eliminated much of the graphite material around the tie rod button and provided a flow of hot gases over the periphery of the protection cup which replaced the skirt, one of the design parameters which had to be corroborated experimentally was the temperature and flow regime around the tie rod button. To study these phenomena, a chromel-alumel thermocouple was imbedded into the tip of the button at the center-line and brazed in place flush with the downstream surface. By comparing this temperature with that of the tie rod gas at the exit of the tube liner, the effects of the new design could be observed by the degree of overheating of the button.

Test 14a was a successfully completed 20 minute cycle at temperatures near 4283°R. Figure 43 shows that after this cycle there was little evident damage except for the small coating chips on the trailing edge of the insulating cup. The thermocouple in the button indicated a steady-state temperature of 1105°R during the test and was not damaged. Unfortunately, a short circuit in the tie rod exit gas thermocouple precluded a direct comparison of the two

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Figure 43

NRX-A5 Skirtless Block After 20 Minutes at 4283°R (HHT-4-14a)

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temperatures as planned. The block and protection cup were firmly stuck together at the coated interface and no disassembly of the support hardware was attempted.

During the second cycle, a failure occurred near the cluster inlet end and overheating of the elements occurred after 10 minutes at full power. Substantial quantities of molten materials were carried through the flow channels and deposited on the support block as shown in Figure 44. The flow of molten materials over the ATJ protection cup chipped and peeled the coating severely. In addition, welding of the block to the overheated elements and subsequent loss of coating on the block during disassembly rendered further testing inadvisable.

The tie rod thermocouple overheated just before the test was terminated and the braze melted. However, both tie rod thermocouples functioned adequately during the steady-state hold at full power. The button material was at 1238°R while the exit gas temperature in the tube liner was 1130°R . The small difference indicates that the effect of the new geometry on the tie rod button temperature was not significant. It should be noted again that both temperatures are higher than would be expected in the NRX-A5 test because of the HHT-4 test configuration.

Figures 45 through 47 show several views of the support components. These illustrate the fact that, with the exceptions of the depositing of foreign materials the welding to the elements, and the erosion damage, little actual physical damage was sustained. The insulating cup lost only 6 percent of its weight and much of the coating was still adherent. The protection cup shows

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Figure 44
NRX-A5 Skirtless Block After Cluster Failure (HHT-4-14b)

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Figure 45

NRX-A5 Skirtless Block After 30 Minutes at 4283°R (HHT-4-14b)

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Figure 46

NRX-A5 Skirtless Block After 30 Minutes at 4283°R (HHT-4-14b)

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Figure 47

Insulating Cup After 30 Minutes at 4283°R (HHT-4-14b)

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only minor corrosion in the area where peeling of coating occurred indicating that the coating failure occurred just prior to shut-down. On the side of the block where no molten materials flowed, no coating damage or corrosion was observed on either the block or cup.

Sectioning of the block and cup corroborated the earlier indications that very little sub-coating damage occurred. Figures 48 and 49 show several views of the block in section. These also illustrate the welding which occurred between the block and cup and between the support washer and cup. Note that the bores are essentially undamaged in spite of the erosive flow of molten material through the block.

8. HHT-4-15

This test was a second attempt to endurance test the skirtless block configuration for 40 minutes at 4283°R following the termination of the previous test series because of a cluster failure. Two cycles of 10 and 5 minutes respectively were successfully completed with normal shut-downs. In both cases cluster failures near the inlet end resulted in small temperature excursions which prevented further testing; however, in both cases, the tests were terminated sufficiently soon to prevent physical damage to the block. Figures 50 and 51 shows the block and support hardware after these cycles. After the second cycle some cracking of the coating on the ATJ protection cup and some lifting of the coating on the trailing edge of the insulating cup were observed.

In the third cycle, a failure in the cluster similar to that in HHT-4-14 resulted in test termination after a cumulative test time of 21.6 minutes for the three cycles. The center element and fuel elements were overheated and, again,

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Figure 48

Sectional Views of the Skirtless Block, Cup, and Washer After 30 Minutes at 4283°R (HHT-4-14)

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Cup to Top of Washer

Cup to Block

Figure 49

40X Views of Weld Joints Between Cup, Block, and Washer (HHT-4-14)

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Figure 50

NRX-A5 Skirtless Block After 10 Minutes at 4283°R (HHT-4-15a)

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Figure 51

NRX-A5 Skirtless Block After 15 Minutes at 4283°R (HHT-4-15b)

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molten materials from the cluster flowed through the block coolant channels and center bore. The tube liner melted over the tie rod button and support cone, and the coating on the protection cup peeled rather severely. Molten materials were, as previously deposited on the block. Figures 52 and 53 shows two views of the support hardware following the final test cycle.

As in the previous test, no gross physical damage was evident after the test with the exception of that caused by the molten materials. Because of the large areas of exposed graphite, no further testing was accomplished. After sectioning, the sub-coating condition of the block, washer, and cup was excellent. Figures 54 through 56 show sections including the weld joints between the cup, block, and washer. One can also see areas of deposited material between the cup and support washer. This material is probably from the melted tube liner.

9. HHT-4-16, 17

The last two tests were additional attempts to endurance test the skirtless block configuration for a full 60 minutes. In both tests the cluster failed on the initial power ramp. Based on the consistent deterioration in the lengths of the test cycles over the last several tests, further testing was postponed to facilitate a complete investigation into the causes of cluster failure. Preliminary results of this investigation and the corrective actions taken were discussed previously in Section II of this report.

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Figure 52

NRX-A5 Skirtless Block
After 22 Minutes at 4283°R and Cluster Failure (HHT-4-15c)

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Figure 53

NRX-A5 Skirtless Block and Support Components
After Final Cycle (HHT-4-15c)

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Figure 54

Sectional Views of the Skirtless Block, Cup, and Washer
After 22 Minutes at 4283°R (HHT-4-15)

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Cup to Block

Cup to Side of Washer

Figure 55

40X Views of Weld Joints Between Cup and Washer (HHT-4-15)

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40X

200X

Figure 56

Weld Joint Between Washer and Cup (HHT-4-15)

IV. SUMMARY AND CONCLUSIONS

The development of hardware, procedures, and techniques for testing full clusters at power levels about 35 percent of those of NRX-A5 reactor test clusters was given special emphasis during the testing of support components for NRX-A4 and NRX-A5 tests. The state-of-the-art of cluster testing has reached a level at which many of the basic problems associated with this component test configuration have either been solved or analyzed to the extent that solutions can be effected. Test cycles of 20 minutes have been attained repeatedly; furnace control based on exit gas temperature has been refined; arcing in the cold and hot end chucks has been alleviated; instrumentation for accurate tie rod strain and tie rod exit gas temperature measurements have been included in the test configuration; and severe element bowing and cracking have been alleviated with improvements in the orificing technique and support hardware. Furthermore, the efficiency of assembly and testing of clusters has been substantially increased by the incorporation of standardized assembly and test procedures, inventory controls, and flow system improvements.

The experience obtained during the test series presented herein has pointed the way to the solution of several problems inherent to the test configuration and test conditions which remain to be solved. Cold end chucking is being developed to provide for relatively unhindered axial movement and limited radial movement of the cluster during thermal growth. An expandable hot end chuck is also being developed to provide for radial growth of the elements. The hydrogen inlet is being improved by the addition of an inlet plenum which separates hydrogen and helium flows. Finally, improvements in the lateral support system will provide for adequate support while also allowing limited radial expansion.

The support block and components testing program in support of NRX-A4 and NRX-A5 reactor test designs proceeded concurrently with the development of the cluster test itself. Twenty-one cluster tests were completed during this series. These tests were directed toward the following design objectives:

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1. Investigation of the support block cracking phenomena noted in NRX-A3.
2. Study of the endurance capability of NRX-A3, NRX-A4, and NRX-A5 blocks which contained cracks in the counterbore radius.
3. Alleviation of the influence of the cracking phenomena in NRX-A5.
4. Endurance testing of the skirtless support block.
5. Testing of the adequacy of exit gas thermocouples and related hardware for use in NRX-A5.

The first objective was briefly encountered then set aside until further refinements in test techniques could be made. In order to simulate the NRX-A3 counterbore cracking, high mechanical loads and high thermal stresses must be set up in the support block. To accomplish this, high thermal ramps on the order of 50 to 150 degrees Rankine per second are required. In addition, the use of a cryogenic gas at the inlet to the cluster and the use of an efficient shroud-reflector to minimize heat losses from the periphery of the block both would be desirable. None of these conditions could be met adequately within the present state-of-the-art; however, plans are being formulated for the eventual upgrading of the cluster test to provide this high-transient capability.

The effect of a pre-existing counterbore crack on support block life was studied in several tests. A 37 minute endurance test of a pre-cracked NRX-A4 block at 4280°R indicated that, in spite of severe corrosion of the support washer and block in the counterbore area, the adequacy of the support system was maintained. The results of this test, with other pertinent data, were used to establish the endurance capability of the NRX-A4 support system. In addition, the test pointed out the need for a new support washer design for NRX-A5.

The use of pyrofoil washers underneath a coated ATJ graphite support washer was suggested as a means of preventing the cracking of blocks or to minimize the corrosion of the blocks if cracking occurred. Tests of up to 40 minutes at 4283°R showed that no excessive corrosion

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damage was sustained by the foil washers, by the ATJ support washers, or by the blocks. This data contributed to the decision to employ this support configuration in NRX-A5.

The objective of endurance testing the skirtless block was not fully attained because of cluster failures. In two tests of 22 and 30 minutes at 4280°R , both the blocks, washers, protection cups, and insulating cups were essentially untouched except for loss of coating. This loss was presumably a result of erosion by molten materials from upstream in the damaged cluster. Welding of the support blocks, washers, and cups was observed in both tests. A review of these results along with other analytical and experimental data resulted in the release of this design as an NRX-A5 experiment.

Exit gas thermocouple designs were tested in two tests of approximately 40 minutes equivalent time at 4283°R . In the first, a high temperature excursion because of inadequate furnace control melted the thermocouple after several minutes. In the second the thermocouple operated as expected for 20 minutes in one cycle and for about 6 minutes in a second cycle before it failed. In both tests, severe loss of material occurred on the insulating cup. In spite of this fact, the adequacy of the support system was unimpaired in both 40 minute tests. However, because of this severe corrosion damage to the cup, the design was not released for use in NRX-A5.

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APPENDIX A

METHOD FOR APPROXIMATING EQUIVALENT CORROSION TIME
FROM EXPERIMENTAL DATA

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In many cluster tests, the steady-state condition is never really achieved. This is a result of inaccurate control, changes in flow and current which take place during the test as a result of corrosion, and other causes of temperature variations with time. Graphite corrosion occurs during these transient states at rates which are related to the material temperature. If the transient-state corrosion can be referred to a reference temperature, then the time logged at this reference temperature becomes a convenient tool for comparing different tests as well as determining the effect of transient states.

Assuming a rate reaction of graphite removal in the form of

$$dm/dt = -C_1 e^{-E/RT}$$

where

- E = activation energy
- R = gas constant
- T = temperature
- t = time
- m = mass

a test of duration from $t = 0$ to $t = t_o$ would produce

$$M_o - m = \int_{M_o}^m dm = \int_0^{t_o} C_1 e^{-E/RT} dt$$

where

$$T = f(t)$$

The same weight loss would occur for a fixed reference temperature, T_r , at a duration t_r

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$$C_1 e^{-E/RT_r} \cdot tr = \int_{M_o}^m dm = \int_0^{to} C_1 e^{-E/RT} dt$$

or

$$tr = e^{E/RT_r} \int_0^{to} e^{-E/RT} \cdot dt$$

or

$$tr = \int_0^{to} dt \cdot e^{\frac{E}{R} \left(\frac{1}{T_r} - \frac{1}{T} \right)}$$

where the reference temperature is T_r and the measured temperature is T .

From graphite corrosion measurements, the best value at present of $E/R = B$ is: ⁽⁴⁾

$$\frac{30,000 \text{ cal/mole}}{1.987 \text{ cal/mole } ^\circ\text{K}} = 15,100^\circ\text{K} = 27,200^\circ\text{R}$$

Therefore, the last equation can be rewritten in dimensionless form as

$$tr/to = \int_0^{to/to} d(t/to) \cdot e^{27,200 \left(\frac{1}{T_r} - \frac{1}{T} \right)}$$

where

$$\eta = t/to$$

and if

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$$Y = e^{27,200 \left(\frac{1}{T_r} - \frac{1}{T} \right)}$$

$$t_r/t_o = \int_0^1 Y d\eta = \bar{Y} \int_0^1 d\eta = \bar{Y}$$

Using Simpsons rule (Parabolic Rule) for an even number (2n) of spaces in the interval of $\eta = 0$ and $\eta = 1$ yields the approximation to the integration as

$$t_r/t_o = \bar{Y} = \frac{Y_o + 4Y_1 + 2Y_2 + 4Y_3 + \dots + 2Y_{2n-2} + 4Y_{2n-1} + Y_{2n}}{6n}$$

Hence, n can be any convenient integer to insure that an even number of spaces 2n exist between $\eta = 0$ and $\eta = 1$. The equivalent time t_r at reference temperature T_r is then exactly equal to

$$t_r = \bar{Y} t_o$$

where t_o is the actual test time.

DESCRIPTION OF INPUT DATA

The following steps must be followed when inputting data:

1. Experimental temperature readings must be taken at equal time intervals, where the number of temperature readings must be odd.
2. The first card for each test series contains the following:

T_n	= Test number	Cols. 1-12
R	= Number of temperature readings (always odd)	Cols. 13-24
Time	= Actual time of test period (min.)	Cols. 25-36
Ref	= Reference temperature ($^{\circ}R$)	Cols. 37-48

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3. The next series of cards contain one temperature ($^{\circ}\text{R}$) reading per card,

Cols. 1-12

There must be R cards in each series.

4. Test number input format is an A field. All other input values must contain a decimal point.

OUTPUT DATA

The program was written to print out the following information:

Actual test time (min.)

Equivalent corrosion time (min.)

Given reference temperature ($^{\circ}\text{R}$)

List of input temperatures ($^{\circ}\text{R}$)

A copy of the program and a sample of input and output data sheets follow.

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APPENDIX B

COMPONENT IDENTIFICATION

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COMPONENT IDENTIFICATION

COMPONENT	HHT-4 TEST NUMBER										
	7	8a	8b	9a	9b	9c	10a	10b	10c	11a	12a
B Element						AC-49-20335	AC-59-20844	AC-59-20842	AC-69-21365	AC-59-23050	AC-59-22977
C Element						AC-79-21427	AC-59-20808	AC-69-20945	AC-89-21687	AC-59-23054	AC-49-22971
D Element						AC-89-23328	AC-59-20838	AC-59-20815	AC-89-21756	AC-59-23049	AC-59-22975
E Element						AC-79-21540	AC-59-20801	AC-59-17757	AC-89-21796	AC-59-23048	AC-59-22982
F Element						AC-79-23209	AC-59-20818	AC-59-17754	AC-79-18033	AC-59-23051	AC-59-22973
G Element						AC-89-23318	AC-59-20802	AC-59-17732	AC-79-17992	AC-59-23053	AC-49-22969
Support Block	HT-1901	A-22026	A-22026	A-22062	A-22062	A-22062	A-31733	A-31733	A-31733	A-21944	A-21370
Insulating Cup											(LB1855) 28
Insulating Washer											(LB1590)
Support Washer											RHL88-8 PC. 1
Protection Cup											
Tie Rod							801	681	7T		76G
Exit Gas Thermocouple											
Tube Liner Thermocouple											A-22239
Tie Rod Button Thermocouple											

() = Lot Number

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COMPONENT IDENTIFICATION

COMPONENT	HHT-4 TEST NUMBER									
	13a	13b	14a	14b	15a	15b	15c	16a	16b	17a
B Element	AC-59-22986	AC-59-22989	AC-59-23002	UN-99-96864	AC-59-23023	AC-69-23079	AC-79-23180	UN-99-97502	AC-69-29330	AC-69-29250
C Element	AC-69-23087	AC-59-22920	AC-59-23009	UN-99-98246	AC-59-23020	AC-69-23091	AC-59-23024	UN-99-97649	AC-69-29328	AC-69-29254
D Element	AC-69-23122	AC-49-22937	AC-59-23001	UN-99-96672	AC-59-23018	AC-59-23027	AC-69-21049	UN-99-97409	AC-69-29334	AC-69-29252
E Element	AC-69-23081	AC-69-23074	AC-59-23006	UN-99-96810	AC-59-23041	AC-69-23078	AC-59-23036	UN-99-97784	AC-69-29259	AC-69-29263
F Element	AC-59-23005	AC-49-22926	AC-59-23008	UN-99-96903	AC-59-23031	AC-69-23055	AC-69-20946	UN-99-97625	AC-69-29333	AC-69-29262
G Element	AC-69-23090	AC-59-22997	AC-59-23016	UN-99-96916	AC-59-23029	AC-69-23070	AC-59-23032	UN-99-97848	AC-69-29314	AC-69-29265
Support Block	A-17743	A-17743	A-33203	A-33203	A-33167	A-33167	A-33167	A-33178	A-33178	A-33085
Insulating Cup	(43-74) 15	(43-74) 15	(LB1855) 34	(LB1855) 34	(LB1855) 39	(LB1855) 39	(LB1855) 39	(LB885) 39	(LB885) 39	(LB1885) 24
Insulating Washer			SP-3	SP-3						(LB1590)
Support Washer	(LB2372) 4	(LB2372) 4	(LB2288) 3	(LB2288) 3	(LB2288)	(LB2288)	(LB2288)	(LB2304) 13	(LB2304) 13	(LB2304)
Protection Cup					(LB2287)	(LB2287)	(LB2287)	(LB2305) 15	(LB2305) 15	(LB2305)
Tie Rod	45U	45U	32 I	32 I	14H	14H	14H	3UH	28G	28G
Exit Gas Thermocouple	A-48863	A-48863								
Tube Liner Thermocouple	A-33286	A-33286	A-33284	A-33284	A-49032	A-23457	A-23457	10	A-49044	A-49044
Tie Rod Button Temperature			A-33283	A-33283						

() = Lot Number