PATHFINDER ATOMIC POWER PLANT

Summary Report
 SHUTDOWN COOLING TEST
 by W. E. Littleton and W. Ross
 Submitted to

U. S. ATOMIC ENERGY COMMISSION
 NORTHERN STATES POWER COMPANY
 and
 CENTRAL UTILITIES ATOMIC POWER ASSOCIATES
 by

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 Allis-Chalmers Mfg. Co. & Northern States Power Co.
 under
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Reviewed by *R. G. Michel*

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Larry E. Williams
 Authorizing Official
 Date: 06/15/2006

Approved: *W. M. Hawkins*
 W. M. Hawkins
 Mgr., Research and Development
 Nuclear Power Dept.-Greendale

Approved: *C. B. Graham*
 C. B. Graham
 Manager
 Nuclear Power Dept.-Greendale

ALLIS-CHALMERS MANUFACTURING COMPANY
 ATOMIC ENERGY DIVISION
 MILWAUKEE 1, WISCONSIN

Approved: *Hibbert Hill*
 Hibbert Hill
 Chief Engineer

NORTHERN STATES POWER COMPANY
 15 SOUTH FIFTH STREET
 MINNEAPOLIS 2, MINNESOTA

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ACNP-6124
December 15, 1961

Summary Report

PATHFINDER SHUTDOWN COOLING TEST

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W. E. Littleton
W. E. Littleton

W. Ross
W. Ross

Allis-Chalmers Mfg. Company
Nuclear Power Dept.-Greendale

FOREWORD

One of a series of reports on research and development in connection with the design of Pathfinder Atomic Power Plant, this particular report deals with the "Shutdown Cooling Test."

The Pathfinder plant will be located at a site near Sioux Falls, South Dakota and is scheduled for operation in June, 1962. Owners and operators of the plant will be Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development and design as well as being responsible for plant construction.

The U. S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program.

The plant's reactor will be of the Controlled Recirculation Boiling Reactor type with Nuclear Superheater.

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I. INTRODUCTION

The Pathfinder Atomic Power Plant incorporates an integral nuclear superheater in a water-moderated boiling-water thermal reactor. The water moderator surrounding the superheater outer insulating tubes is cooler than the superheated steam. The flow of heat to this water must be minimized during operation in the power range. The steam supply to the superheater comes from an adjacent boiler section. During shutdown this steam flow ceases. Since the superheater fuel is still generating "decay" heat, the rate of heat flow to the adjacent moderator water must be sufficient to ensure that superheater element temperatures are below acceptable maximum temperatures.

A thin annulus of stagnant steam is used in the Pathfinder superheater to control the heat flow to the moderator water. To select the steam gap (and thus the heat flow rate), it is necessary to establish accurately the relation of the heat flow rate to the superheater fuel element temperature. The Pathfinder Shutdown Cooling Test was performed in order to establish this relation.

A total of three test sections were built and tested. The data from each of the three tests were found to be reproducible within experimental error. The first section was destroyed by stress corrosion due to a high chloride content in the steam medium. The second test section was a simplified and improved test section which provided excellent data within a narrow range of temperature; but thermocouple failures prevented this test from covering the entire range of variables.

The third test section was similar to the second except that most of the thermocouples were eliminated. The entire range of variables, however, was covered - although less information was obtained than had been originally anticipated.

2. TEST APPARATUS

The Pathfinder superheater fuel element is composed of two concentric fuel tubes centered about a poison rod. This integral assembly is inserted into an insulating container. This insulating container is composed of two concentric tubes that are sealed together at the top and are open at the bottom - providing for an insulating layer of stagnant steam between these tubes. The insulating tube unit is surrounded by the saturated water moderator. The geometry is such that when the fuel element is inserted into the insulating tube, three concentric annular steam flow passages are formed. The steam flowing in the outer passage receives heat from the outer surface of the outer fuel tube. The steam flowing in the middle channel receives heat from the inner surface of the outer fuel tube and the outer surface of the inner fuel tube. Finally, the steam in the inner flow channel receives heat from the inner surface of the inner fuel tube.

The test sections for the shutdown cooling test were intended to mock up the Pathfinder fuel element as closely as possible and still allow space for instrumentation. The test was performed in a pressure vessel at reactor conditions of 600 psig. By using external strip heaters,

it was possible to provide a saturated water moderator external to the insulating tube assembly as well as saturated steam above and below the test sections. In order to minimize the net flow of steam through the test section, nichrome wire was wrapped around the bottom flange. This prevented the superheater steam from condensing on the cooler surface. Fig. 1 shows the entire assembly.

3. PRESSURE VESSEL

The pressure vessel was fabricated from 6 in., schedule 40, ASTM A53-54 TGRA seamless steel pipe (Fig. 2). It was made of two welded sections in order to facilitate the installation of a support ring upon which the test section rested. The support ring also served to separate the steam and water phases at the bottom of the vessel. Six Chromalox strip heaters, with a total rating of 14 kw, provided the energy to heat the vessel to operating conditions and to make up heat losses during operation. A cooling coil was provided around the top end of the vessel to allow for finer pressure control. Numerous penetrations were made in the vessel for installation of thermocouples, pressure taps, makeup water inlet, and the level sight gage (Fig. 3).

The pressure vessel was suspended from a triangular test stand assembly (Figs. 4 and 5). A drain valve and a pressure relief valve were installed on the bottom blank flange. A motor-driven pump was connected to the makeup water inlet line. System pressures were checked with a zero to 1000 psig gage. The pressure vessel assembly was completely wrapped with 2 in. of insulation.

4. POWER SUPPLY

The test section was electrically heated by power supplied from a d.c. motor-generator set rated 12 volts at 1250 amperes, or 6 volts at 2500 amperes.

5. TEST SECTIONS

A. TEST SECTION NO. 1

Four type 304 stainless steel tubes, simulating the fuel tubes of the element and insulating tube, were assembled as shown in Figs. 6 and 7. The stainless steel poison rod was coated with high-temperature insulating enamel and installed inside of the inner fuel tube. The inner and outer fuel tubes were spaced by means of ceramic screws and thermocouple wires. The thermocouples were circumferentially fixed to the surface with high-temperature silver solder at points 120° apart. Two thermocouples were attached to the inner fuel tube and two more to the inside of the outer tube. The insulating gap was maintained by three wires. The inner and outer insulating tubes were sealed together at the top of the section but were open at the bottom - to provide an inlet to the stagnant steam space.

The inner and outer fuel tubes were heated electrically through individual flexible copper leads connected to a common bus bar connector. The common bus bars were electrically

insulated...gasketed...and held in place between the flanges on either end of the vessel.

B. TEST SECTION NO. 2

From experience gained with Test Section No. 1 it was possible to design an improved version of the test section. Several major changes were made. The design of the end connectors was improved and the surface temperature thermocouples were attached to the tubes with Sauerlesen cement instead of silver solder. The electrical insulation of thermocouples was accomplished by using a high-temperature glass-braided insulation over the thermocouple's leads. Details of the top and bottom end assemblies are shown in Figs. 8 and 9. Ceramic screws were again used to space the tubes. The poison rod was eliminated and the ceramic screws passed entirely through the fuel tubes - as shown in Fig. 10. The spacer wires were removed from the insulating tube gap - with the gap maintained by spacers at the top and bottom of the tube. The use of two end-connector bus bars on each end, connected independently to inner and outer fuel tubes, allowed for the possibility of heating each fuel tube independently.

C. TEST SECTION NO. 3

The third test section was essentially a duplicate of Test Section No. 2. However, no surface thermocouples were used in Section 3.

Instead, a 1/4-in. ceramic-coated stainless steel tube was welded into the central fuel tube. Three inconel sheathed chrome-alumel thermocouples were inserted into this small tube. Each of the three thermocouples measured the peak element temperature at a different axial location. The elements were spaced by means of ceramic screws inserted into the various tubes in the same manner as in Test Section No. 1 - but without the use of spacer wires.

6. TEST PROCEDURE

The test section was installed in the pressure vessel - and the vessel was then sealed and hydrostatically tested to 1500 psi. Following this, the vessel was filled to the proper level (as indicated on the sight glass) with deionized water. The strip heaters and flange heater were then turned on. After pressure in the system reached 300 psi, the bottom valve was opened to flash steam to the atmosphere - purging the air from the system. The valve was closed when pressure dropped to 100 psig. The flashing operation was repeated once more when the system reached 300 psi. Power to the auxiliary heaters was reduced at 550 psig and the pressure coasted up to 600 psig. Varying the power to the auxiliary heaters made it possible to arrive at a steady-state pressure of 600 ± 5 psig. The saturated water and steam temperature was ~489 F at this point.

After holding the steady-state conditions for approximately one-half hour, the motor-generator set was turned on at its lowest power setting. The instruments were carefully watched until steady-state was again reached. During this period, however, it was necessary to reduce the power to the auxiliary heaters in order to maintain the 600 psig atmosphere. Once the steady-state condition was reached, it was maintained for at least ten minutes before instrument readings were recorded on the data sheets. The following readings were taken:

- a. System pressure
- b. Water temperature
- c. Steam temperature in dome
- d. All surface temperatures
- e. All channel steam temperatures
- f. Voltage across test section
- g. Current through each tube
- h. Power to auxiliary heaters

After these readings were taken, power input was increased at such a rate that tube surface temperature rose at the rate of approximately 200 F/hr.

7. THEORETICAL

Prior to running the Shutdown Cooling Test, a mathematical model was developed in order to describe the heat transfer in the Pathfinder superheater element at no-flow conditions. Since no steam is flowing through

the channels, the radial heat transfer can be attributed to thermal radiation and conduction. In long thin passages of the type under consideration, free convection is of little significance and can be conservatively neglected. The following assumptions were used in developing the mathematical equations.

- a. The element is at steady-state.
- b. The temperature drop across the thin metal tubes is negligible in the radial direction...i.e., $K\infty$.
- c. The peak temperature occurs on the inner fuel tube.
- d. Adiabatic centerline. (The poison tube would also be at the peak fuel element temperature.)
- e. No axial or angular temperature gradient.
- f. The steam temperature in a channel is equal to the arithmetic average of the wall temperatures of the channel.
- g. Forty per cent of the total elemental heat generation takes place in the inner fuel tube (as per data obtained for the Pathfinder fuel element).
- h. Temperatures of the outer insulating tube = 490 F = 950 R.

The following set of equations may be used to describe the heat flow in the element (Fig. 11).

$$q_I = \frac{\sigma A_I (1 - \alpha_I) (\tilde{T}_1^4 - \tilde{T}_2^4)}{(1/\Sigma_I) + (A_I/A_2) \left(\frac{1}{\Sigma_2} - 1\right)} + \frac{2\pi k_I (T_1 - T_2)}{\ln (R_2/R_I)}$$

$$q_{II} = \frac{\sigma A_2 (1 - \alpha_{II}) (\tilde{T}_2^4 - \tilde{T}_3^4)}{(1/\Sigma_2) + (A_2/A_3) \left(\frac{1}{\Sigma_3} - 1\right)} + \frac{2\pi k_{II} (T_2 - T_3)}{\ln (R_3/R_2)}$$

$$q_{II} = \frac{\alpha A_3 (1 - \alpha_{III}) (\tilde{T}_3^4 - 8145)}{(1/\Sigma_3) + (A_3/A_4) \left(\frac{1}{\Sigma_4} - 1 \right)} + \frac{2\pi k_{III} (T_3 - 490)}{\ln (R_4/R_3)}$$

$$q_I = 0.4 q_{II}$$

and,

$$\alpha = \alpha_H + \alpha_C$$

$$\alpha_H = C_S \Sigma_S (\tilde{T}_S/\tilde{T}_H)^{.45}$$

$$\alpha_C = C_S \Sigma_S (\tilde{T}_S/\tilde{T}_C)^{.45}$$

$$\tilde{T}_S = (\tilde{T}_H + \tilde{T}_C)/2$$

$$\Sigma_S = \phi [T_I P_S L (T/T_S)]$$

$$C_S = f[(P_S + P_T)/2 P_S L]$$

$$\tilde{T}_S = T + 460$$

where

q = Heat generation rate

σ = Steffen-Boltzman constant

A = Heat transfer surface area

$\tilde{T}$ = Temperature - $^{\circ}R$

T = Temperature - $^{\circ}F$

α = Steam absorptivity

Σ = Surface emissivity

R = Radius

k = Thermal conductivity of steam

Σ_S = Total steam emissivity

C_s = Pressure correction factor

P = Pressure

Subscripts

(See Fig. 11)

H - Hot surface

1 - Inner Fuel Tube

c - Cold surface

2 - Outer Fuel Tube

s - Steam

3 - Inner Insulating Tube

T - Total

4 - Outer Insulating Tube

Thus there are four basic equations available to solve for the values of T_1 , T_2 , T_3 , q_1 , and q_2 . If a value of T_1 is assumed, it is possible to solve for the remaining unknowns. The most convenient method of solution is by a systematic trial and error technique. The results of these hand calculations are presented in Fig. 12.

8. TEST RESULTS

This section will be limited to stating what occurred in the testing of each test section. It should be mentioned that - although none of the tests can be considered an unqualified success - significant information was obtained from each test section and incorporated into a fairly conclusive and reproducible body of evidence for use in designing the reactor fuel element.

TEST SECTION NO. 1:

Results of the first section are presented in Fig. 13. The data obtained early in the testing operation appeared to be consistent.

After a few days operation, it became increasingly difficult to attain and hold steady-state conditions...and unaccountable surface temperature fluctuations occurred. It was decided to suspend testing and dismantle the test section for inspection.

Visual inspection showed that the test section was severely damaged. In several locations, holes were found in the fuel tubes. Many of the thermocouples had been pulled loose from the surface of the tubes. It was postulated that the major damage to the tubes was caused by stress corrosion of the stainless steel - due to the presence of chloride ions in the steam and water phases. City water had inadvertently been introduced into the system instead of deionized water...and further investigation revealed that the pressure vessel had been cleaned with trichloroethylene prior to assembly. Differential longitudinal expansion probably caused the thermocouples to become separated from the tube surfaces. It was also noted that hot spots developed in the end-connector assemblies due to insufficient heat dissipation and high contact resistance.

TEST SECTION NO. 2:

Results obtained from the second test section are presented in Fig. 14. It was felt that these data were both consistent and accurate, but did not extend far enough into the high power range. As power to the test section was increased, the incidence of

thermocouple failure also increased. It was evident that the Sauerlesen cement, used to fasten the thermocouples to the tube surfaces, broke down in the high temperature steam atmosphere.

Testing was continued until no further significant information could be obtained from the test section.

TEST SECTION NO. 3:

Results from the third test section are presented in Fig. 15. A good general trend was obtained from the runs. Some of the data points are questionable - but the curve obtained appears to check out the results from Test Section No. 2. Differential expansion caused failure of the ceramic screw spacers and ultimate shorting of the central thermocouple tube against the inner fuel tube. Pictures of the disassembled element are shown in Figs. 16 to 25. It should be noted that the bottom of the thermocouple tube is burned because of contact with the inner fuel tube (see Fig. 20).

9. DISCUSSION

Although an appreciable amount of scatter in the data points is present, inspection of the composite results (Fig. 26) indicates consistency over the range of interest. Preliminary calculations and assumptions were conservative and were performed primarily for initial design use. Since it was desired to determine the value of maximum temperature in the

element (peak temperature) for a given generation rate, the set of results indicating the highest temperature is the most conservative. From the point of view of shutdown operation, the data obtained from the first test section gave the least conservative interpretation. The lower temperatures obtained in this test may be attributed to the higher effective thermal conductivity caused by the presence of spacer wires and thermocouple wires in the steam gap. The effect of the poison rod in Test Section No. 1 should be negligible unless natural convection could be a major contributing factor. If this did occur, the presence of the poison rod should have decreased the heat dissipation - since natural circulation is reduced in long, thin passages. It appears impossible to separate accurately the effects of the wires and possible natural convection - since neither may be calculated precisely in this particular geometry.

Data from the second test section appears to be only slightly less conservative than that from the third test section. The sections were geometrically identical except that Test Section No. 2 contained several thermocouples in the flow passages. Although these thermocouples were not used for spacing, they undoubtedly influenced the effective thermal conductivity to some degree. Thus it may be concluded that the findings are consistent and logical.

It was decided to use the data from Test Section No. 3, along with appropriate uncertainty allowances, in the design of the Pathfinder fuel element. Assuming only radiation and conductive heat transfer, the

test results can be fitted to a set of equations of the form:

$$q = \frac{\sigma A (T^4 - T'^4)}{\frac{1}{\Sigma} + \frac{A}{A'} \left(\frac{1}{\Sigma'} - 1 \right)} + \frac{2\pi k (T - T')}{\ln \left(\frac{R'}{R} \right)}$$

This is similar to the equations used in the theoretical section - but the allowance for steam being a non-luminous gas has been omitted. The ability to account for a non-luminous gas in a simple fashion was felt to be questionable for the fuel element geometry under consideration. Also, the method of taking the pressure effect into consideration was rather arbitrary. (The value for the $1 - \alpha$ factor in the original calculations varied about 0.65.) Without the gas absorptivity, the only values not readily determined are those for the surface emissivities. The emissivity is dependent upon the type of materials, surface conditions and surface temperatures. They would have different values for each tube and for each run. The assumption was made that the same value of emissivity would be used for all surfaces in the test section. Fig. 27 shows a comparison of the results from Test Section No. 3 with values obtained from the mathematical model using two values of emissivity. Since the high temperature range is of major importance, it was assumed that the emissivity of the tubes was equal to 0.8. Although the value of Σ seems high, this may be due to any non-luminous effects. Thus Σ as used in this study is not a true value for emissivity, but rather an empirical factor used to facilitate the curve fit.

An attempt was made to estimate the heat loss from the superheater fuel element at coolant flow conditions. It is assumed that the inner

insulating tube temperature is equal to the steam temperature in the outer flow channel. For full-power operation, this can be shown to be true to within 20 F. Thus the heat loss from the element is a function of moderator temperature, inner insulating tube temperature, gap thickness, and emissivity.

Again assuming that the heat loss is due entirely to radiation and conduction, and that the emissivity is 0.8 on both surfaces, the heat loss as a function of temperature may be derived. For a 0.057 in. gap, this heat loss function is presented in Fig. 28. The area over which this heat flux is taken is based on the O.D. of the inner insulating tube. In this case it is 0.926 in.

10. CONCLUSION

Results of this test show that the relation between heat flow rate and superheater fuel element temperature can be adequately described for engineering purposes by the mathematical model - as presented in the theoretical discussion - modified by several assumptions. The first modification: that the allowance for a non-luminous gas be omitted... and the second: that the value of 0.8 be used for the emissivity for all surfaces.

Test results have been used to demonstrate the ability of the Pathfinder superheater fuel element to safely dissipate decay heat generated after shutdown - even in the absence of net steam flow.

Fig. 1...Test Apparatus for Pathfinder Shutdown Cooling Test (207757)

QTY	ITEM	DESCRIPTION	MAT'L	UNIT
1	1	TUBE TEST ASSEMBLY		
1	2	TANK ASSEMBLY		
1	3	COVER ASSEMBLY		
1	4	BUS BAR		
1	5	BUS BAR		
6	6	500.1 AND 1/2 THK GASKET	GRAPHITE	TRIA
1	7	TUBE ASSEMBLY		
4	8	6-1/2 O.D. X 1/2 I.D. X 1/8 THK GASKET	DUMMAY	TRIS
1	9	6-1/2 O.D. BLIND FLANGE	STEEL	
1	10	TEST STAND ASSEMBLY		
1	11	1/2" NPT. SCREENED GLOBE VALVE 1/2" NPT. X 1/2" NPT.	STEEL	
2	12	LIQUID LEVEL GAUGE VALVE 1/2" NPT. X 1/2" NPT.	STEEL	
2	13	1/2" SCHED. 40 X 1/2" LG. CLOSE SCREWED PIPE RIFLE	STEEL	
1	14	RELEA. SIGHT GAGE 1/2" NPT. X 1/2" NPT.	STEEL	
1	15	1/2" O.D. X 1/2" THK GASKET	GRAPHITE	TRIA
2	16	3/8" 1/2" NPT. X 1/2" LG. HEA. HD. CAP SCREW	STEEL	
24	17	1" SPRING LOCKWASHER	STEEL	
24	18	1" 1/2" BLIND 2A HUY. SF. HEA. NUT	STEEL	
12	19	1" 1/2" BLIND 2A X 1/2" LG. HUY. SF. HEA. BOLT	STEEL	
6	20	1/2" 22UNC-2A X 1/2" LG. HEA. HD. CAP SCREW	STEEL	
2	21	1" 1/2" BLIND 2A X 1/2" LG. HUY. SF. HEA. BOLT (BY 1/2" TAND 1/2")	STEEL	
1	22	ASSEMBLY & INSTRUMENTATION INSTRUCTIONS		

Fig. 3...Tube Test Assembly (43-500-759)

NO-105-ED					
REV.	IT.	DESCRIPTION	MATERIAL	PART NUMBER	W.K.
	1	TEST STAND ASSEMBLY		43-401-014	100%
	2	FACE PLATE-MIP 1/2 THK. 115 SQ. PLATE	ASTM A7-52T	THIS	002
	3	LEG-MIP 2 1/2 x 3 1/2 (17) 1 10 FLG. ANGLE	ASTM A7-52T	THIS	003
	4	BRACE-MIP 1/2 14 x 1/4 LG. FLAT BAR (LFT 78 IN)	ASTM A7-52T	THIS	004
	5	LUG-MIP 1 1/2 SQ. 12 LG. BAR	STEEL	THIS	005
	6	COATED WELD ROD	STEEL	THIS	006

Fig. 4...Test Stand Details (43-401-014)

Fig. 5...Triangular Test Stand Assembly (207010)

Fig. 6...Tube Assembly - Cross Section (43-024-787)

IT	DESCRIPTION	MATL	QTY REQD	WT.
1	TUBE ASSEMBLY	304-306	501	
2	SEAL GUIDE TUBE ASSEMBLY	35-301-306	501	
3	BUS ROD ASSEMBLY	33-301-408	501	
4	CABLE CONNECTION ASSEMBLY	33-301-408	501	
5	INSULATOR	38-202-781	501	
6	POISON ROD ASSEMBLY	38-202-781	501	
7	TUBE	43-301-162	512	
8	TUBE	43-301-162	512	
9	TUBE	43-301-162	512	
10	TUBE	43-301-162	512	
11	CAP	43-101-126	501	
12	1/4 40NC-34 X 1/4 HELICOILS SAT. 501	5571 16-8	501	
13	BUS. MOD. ASSEMBLY	42-400-780	501	
14	3/8 UNC-27 FIN NET JAMNUTS	BRASS	206-1173	501
15	1/4 40NC-34 X 1/4 HELICOILS SAT. 501	BRASS	43-201-781	501
16	1/4 40NC-34 X 1/4 HELICOILS SAT. 501	BRASS	4008-2495	501
17	BOND		THIS	017
18	015 DIA. SPACING WIRE	015	THIS	018
19	015 DIA. SPACING WIRE	015	THIS	019
20	THERMOCOUPLE LEADS 040 DIA	040	THIS	020
21	BRAZING ALLOY EASY FLOW 445		THIS	021
22	FLUX FOR IT #21		THIS	022
23	CONNECTOR ASSEMBLY	43-201-781	501

NOTE: JOINTS MARKED "X" ARE TO BE BRAZED TOGETHER COAT MATING SURFACES WITH IT 21, 22 AND BRAZE PER EASY-FLO BRAZING SPEC.

NOTE 2:-
COAT END OF IT*5 THAT COMES
IN CONTACT WITH IT*4 & 23 WITH LT*17

Fig. 7...Tube Assembly - Longitudinal View (43-500-757)

Fig. 8...Top - Test Section No. 1 (43-024-791)

Fig. 9...Bottom - Test Section No. 1 (43-024-788)

Fig. 10...Ceramic Screws Through Fuel Tubes (43-024-796)

Fig. II...Heat Flow In Pathfinder Superheater Element (43-024-792)

Fig. 12...Preliminary Model - Heat Dissipation Prediction (43-024-797)

Fig. 13...Test Section No. 1 - Heat Dissipation Results (43-024-793)

Fig. 14...Test Section No. 2 - Heat Dissipation Results (43-024-794)

Fig. 15...Test Section No. 3 - Heat Dissipation Results (43-024-798)

Fig. 16...Assembled No. 3 Test Section

Fig. 17...Test Element and Housing

Fig. 18...Location of White Ceramic Spacer Screws

Fig. 19...From Front to Rear: Ceramic Coated Thermocouple
Tube...Inner Fuel Tube...Outer Fuel Tube...
Housing Containing Insulating Tubes

Fig. 20...Burned-Off Fuel Tube..(Bottom Tube)

Fig. 21...Bus Bar - Lower Assembly

Fig. 22...Upper Bus Bar Assembly in Place

Fig. 23...Upper Bus Bar Assembly Removed from Tube

Fig. 24...Bottom Test Section Flange and
Open End of Insulating Tubes

Fig. 25...Test View of Housing Flange

Fig. 26...Compilation of results from Afterglow Test (43-024-795)

Fig. 27...Emissivity Comparison - Test Section No. 3
vs Two Values from Theoretical Model (43-024-799)

Fig. 28...Heat Loss as a Function of Inner
Insulating Tube Temperature (43-024-800)