WCAP-7288

PWR FLECHT
FINAL TEST PLAN

J. WARING

Westinghouse Atomic Power Divisions

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SECTION 1

TEST PROGRAM

1.1 OBJECTIVE

The objective of the proposed FLECHT test program is to investigate the behavior of a simulated pressurized water reactor core during the core recovery period which follows a loss-of-coolant accident.

The test data will include sufficient information to establish the transient behavior of heat transfer coefficients throughout the test array.

The following specific information will be obtained.

1. Time-temperature behavior of the cladding.
2. Conditions which result in adequate core cooling.
3. Minimum flooding heights at various power densities.
4. Effectiveness of core coolant systems to prevent core damage.
5. Effect of pressure on emergency core cooling capability.
6. Effect of soluble poison on emergency core cooling capability.
7. The effect of cladding damage.
8. Local pressure drop.

1.2 RUN SCHEDULE

The objective of the test program is to determine the effect of several independent parameters on the consequences of the emergency core cooling (ECC) process. The run schedule has been constructed to explore these effects in the ranges of interest. The independent parameters of interest are power density, initial heater rod temperature, flooding rate, coolant temperature and system pressure. The values of these parameters will be varied around a set of reference or "most favored conditions". The following reference parameters have been selected:

1.	Power Density	1.24 kw/ft
2.	Maximum Initial Heater Rod Temperature	1600° F
3.	Flooding Rate	6 inch/second
4.	Coolant Temperature	150° F
5.	System Pressure	60 psia

These parameters correspond to the conditions which are predicted to occur prior to core recovery following a double-ended break on current generation four-loop pressurized water reactors.

The run schedule is divided into three groups according to the type of heater rods to be employed:

Group I: Low peak heater rod temperature using stainless steel clad heater elements with nichrome heating elements.

Group II: High peak heater rod temperature, using stainless steel clad heater elements with molybdenum or Kanthal heating elements.

Group III: High peak heater rod temperature using Zircaloy-4 clad heater elements with molybdenum or Kanthal heating elements.

Final selection of the heating elements to be employed in the Group II and III tests has not been made at this time. The run schedule including all three groups of tests is given in Table 1.

Runs 8 through 12 have been specified as "minimum flooding level" runs. The objective of these runs is to determine the minimum bundle level required to maintain cooling. The procedure for performing these tests is as follows:

1. Fill the test section to 3/4 full (108 inches).
2. Apply power to the bundle.
3. Adjust coolant flow to establish steady state operation at that level.
4. Reduce water level and repeat (3).

TABLE 1

RUN SCHEDULE

Run No.	Initial Temp. (°F)	Flow Rate (in/sec)	Power Density (kw/ft)	Inlet Temp. (°F)	Clad Material	Bundle Size	Pressure (psia)
Group I							
1	1200	6	1.24	150	SS	7 x 7	60
2	1600	6	1.24	150	SS	7 x 7	60
3[a]	1800	6	1.24	150	SS	7 x 7	60
4	1600	18	1.24	150	SS	7 x 7	60
5	1200	6	1.24	150	SS	10 x 10	60
6[a]	1600	6	1.24	150	SS	10 x 10	60
7[a]	1800	6	1.24	150	SS	10 x 10	60
8	Flooding		0.69	150	SS	10 x 10	60
9	Level		0.96	150	SS	10 x 10	60
10	Tests		1.24	150	SS	10 x 10	60
11			1.40	150	SS	10 x 10	60
12			1.24	150	SS	10 x 10	15
13[b]	1600	6	1.24	150	SS	10 x 10	60
14	800	6	1.24	150	SS	10 x 10	60
15	1200	10	1.24	150	SS	10 x 10	60
16	1600	10	1.24	150	SS	10 x 10	60
17	2000	10	1.24	150	SS	10 x 10	60
18	1600	6	0.69	150	SS	10 x 10	60
19	1600	6	1.60	150	SS	10 x 10	60
20	1600	4	1.24	150	SS	10 x 10	60
21	1400	6	1.24	70	SS	10 x 10	15
22	1600	6	1.24	70	SS	10 x 10	15
23	1800	6	1.24	70	SS	10 x 10	15
24	1600	10	1.24	70	SS	10 x 10	15
25	1600	4	1.24	70	SS	10 x 10	15
26	1600	6	1.24	100	SS	10 x 10	60
27	1600	6	1.24	110	SS	10 x 10	30
28	1600	6	1.24	165	SS	10 x 10	75
29	1600	6	1.24	180	SS	10 x 10	90
30	1600	6	1.24	200	SS	10 x 10	60
31	1600	10	1.24	270	SS	10 x 10	60
32	1600	6	1.24	270	SS	10 x 10	60
33	1600	2	1.24	270	SS	10 x 10	60

a. Runs repeated three times.
b. Unheated boundary.

TABLE 1 (Continued)

Run No.	Initial Temp. (°F)	Flow Rate (in/sec)	Power Density (kw/ft)	Inlet Temp. (°F)	Clad Material	Bundle Size	Pressure (psia)
34	1200	2	1.24	150	SS	10 x 10	60
35	1600	2	0.69	150	SS	10 x 10	60
36	1600	2	1.24	150	SS	10 x 10	60
37	1600	2	1.40	150	SS	10 x 10	60
38c	1600	6	1.24	150	SS	10 x 10	60
39d	1600	10	1.24	150	SS	10 x 10	60
40e	1600	10	1.24	150	SS	10 x 10	60
41e	1600	6	1.24	150	SS	10 x 10	60
42	Contingency run						
43	Contingency run						
Early Group III							
44	2000	10	1.24	150	Zr	7 x 7	60
45f	2000	4	1.24	150	Zr	7 x 7	60
Group II							
46	1200	1	1.24	150	SS	7 x 7	60
47	1800	2	1.24	150	SS	7 x 7	60
48	2000	6	1.24	150	SS	7 x 7	60
49	1600	1	1.24	150	SS	7 x 7	60
50	2000	2	1.24	150	SS	7 x 7	60
51	1800	1	0.69	150	SS	7 x 7	60
52	1800	1	1.24	150	SS	7 x 7	60
53	2000	1	0.69	150	SS	7 x 7	60
54	2000	1	1.24	150	SS	7 x 7	60
55	2200	10	1.24	150	SS	7 x 7	60
56	2200	6	1.24	150	SS	7 x 7	60
57	2200	4	1.24	150	SS	7 x 7	60
58	2200	2	0.69	150	SS	7 x 7	60
59	2200	2	1.24	150	SS	7 x 7	60
60g	2200	1	1.24	150	SS	7 x 7	60
61h	2400	6	1.24	150	SS	7 x 7	60
62	Contingency run						
63	Contingency run						
64	Contingency run						
65	Contingency run						

c. Borated Coolant.
d. Mixing Vane Grid.
e. Flow Blockage Test.
f. Run conditions may be re-defined prior to test.
g. This run will be changed to 2000°F and 4 inch/second if beyond Kanthal limits.
h. Run may be changed to 10 inch/second if 6 inch/second is beyond Kanthal limits.

TABLE 1 (Continued)

Run No.	Initial Temp. (°F)	Flow Rate (in/sec)	Power Density (kw/ft)	Inlet Temp. (°F)	Clad Material	Bundle Size	Pressure (psia)
Group III							
66	1600	10	1.24	150	Zr	7 x 7	60
67	1800	10	1.24	150	Zr	7 x 7	60
68i	2000	6	1.24	150	Zr	7 x 7	60
69	2200	10	1.24	150	Zr	7 x 7	60
70	2200	6	1.24	150	Zr	7 x 7	60
71	2200	2	1.24	150	Zr	7 x 7	60
72i	2400	6	1.24	150	Zr	7 x 7	60

i. Run may be changed to 10 inch/second if 6 inch/second is beyond Kanthal limits.

The water level is reduced in 36-inch increments until it is 1/4 full. A maximum thermocouple reading of 1900°F will not be exceeded during this particular test series.

Five runs will be performed to study the special effects of:

1. Unheated boundary
2. Borated coolant
3. Mixing vane grid
4. Flow blockage

These are noted in the run schedule.

Three separate runs will be repeated three times to establish the reproducibility of the test behavior. The runs on which these repeat tests will be performed are Group I runs 3, 6, and 7.

1.3 TEST BUNDLE DESCRIPTION

1.3.1 Geometry

The geometry of the test bundle will correspond to that typical of pressurized water reactor fuel assemblies as follows:

1. Heater Length - 12 feet, heated length.
2. Heater Pitch - 0.563 inches, square pitch.
3. Heater Diameter - 0.422 inches.
4. Control Rod Thimble Diameter - 0.545 inches.
5. Instrumentation Tube Diameter - 0.463 inches.

The array size will simulate a part of the 15 x 15 PWR assembly and will vary from 7 x 7 to 10 x 10 for reasons discussed below.

Flow distribution in the fuel bundle is determined by the local power distribution. In order to properly simulate flow distribution (radial flow), the local power distribution in the test bundle should simulate that of a reactor fuel assembly. Figure 1 shows a quarter section of a typical PWR assembly including the local power distribution. Since the fuel assembly has eight-way symmetry, the quarter section is representative of the full assembly.

A 10 x 10 assembly, to simulate a PWR assembly quarter section, is shown in Figure 2. This bundle satisfies the criterion of a 1.1 radial peaking factor and simulates the local power distribution of a PWR fuel assembly. It is to be noted that non-power-producing elements are included in the test array and are positioned in a manner identical to that of the actual PWR assembly. All types of flow channels encountered in actual PWR assemblies (characterized by power and flow) are included in this mockup. The flow housing which surrounds the test bundle will be heated to minimize the possibility of perturbations in the flow distribution due to cold-wall effects.

The total cost of the FLECHT program is strongly dependent upon the number of heater rods in the test assembly. It is desirable, therefore, to reduce the size of the test array for a large portion of the testing program. A 7 x 7 array, as shown in Figure 3 can be utilized to retain the essential

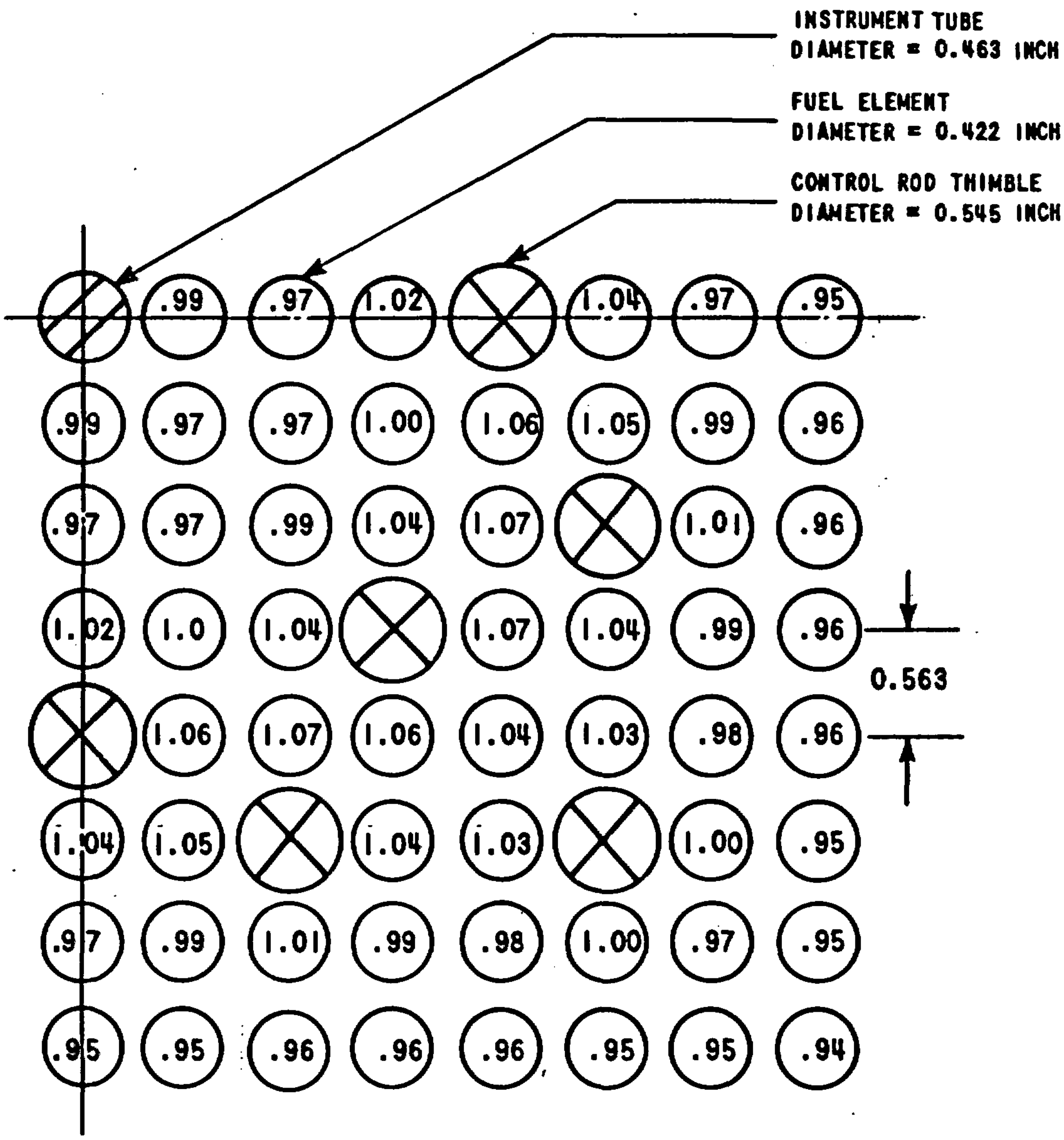

Figure 1. Quarter Section of a Typical PWR Assembly and Power Distribution

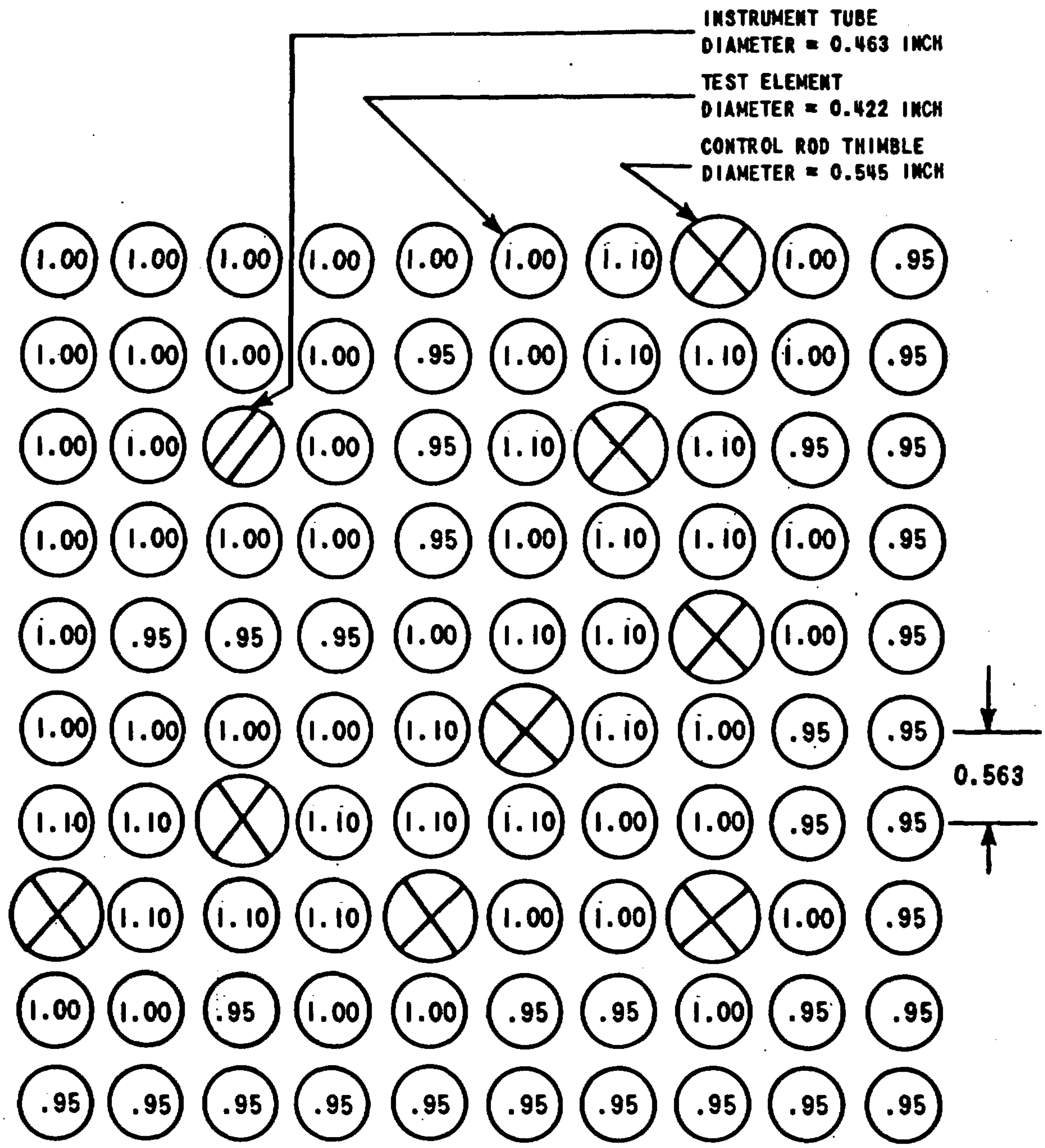

Figure 2. 10 x 10 Test Section Simulating a PWR Assembly and Power Distribution

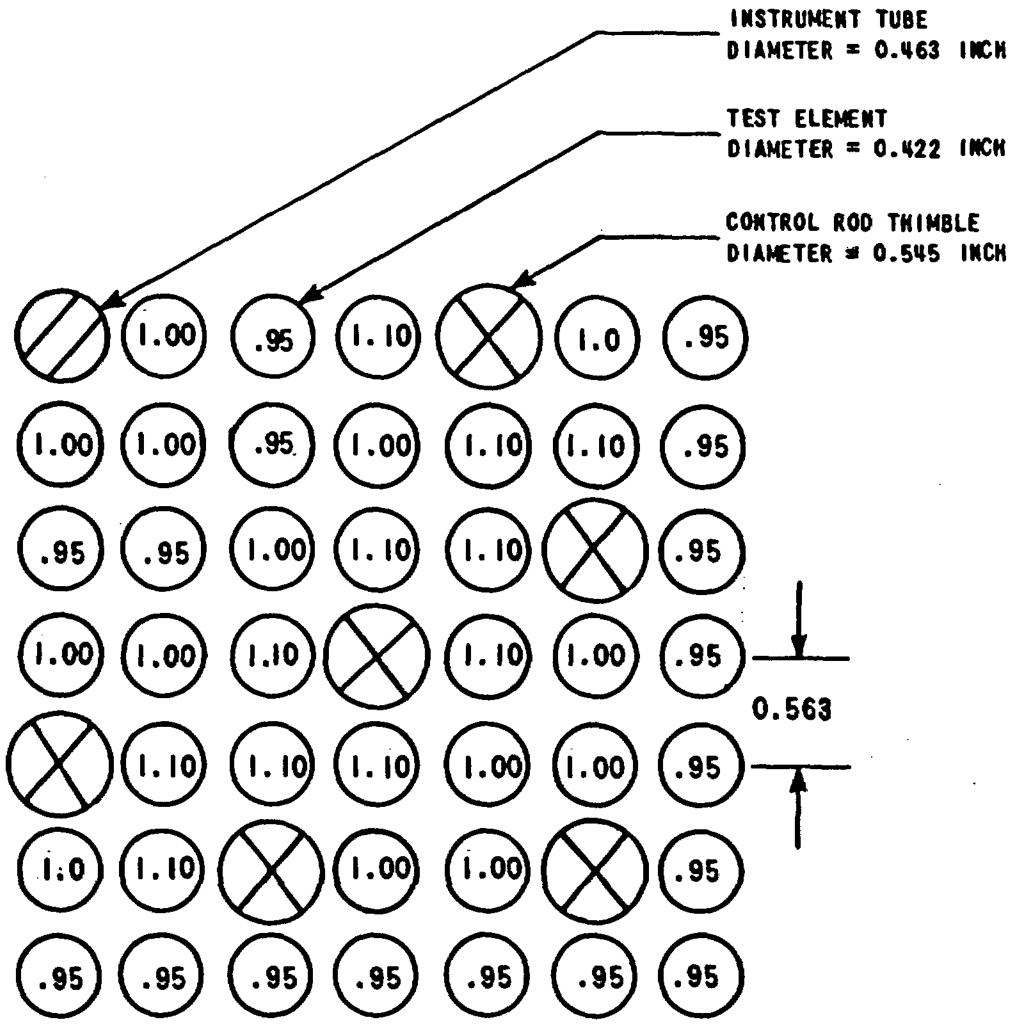

Figure 3. 7 x 7 Test Section Simulating a PWR Assembly and Power Distribution

features of the PWR fuel assembly. Two rows of rods from the 10 x 10 array which duplicated the quarter symmetry were eliminated, as were the low power peripheral rods, since the heated flow housing compensates for these peripheral elements. Since the remaining configuration is identical to the inner portion of the PWR assembly quarter section, it adequately simulates a PWR assembly.

Any difference in performance between the 10 x 10 and 7 x 7 arrays will be accounted for since tests will be performed using both bundles. However, the bulk of the test program will be performed with the 7 x 7 array. These arrays are compared schematically with the PWR array in Figure 4.

Heater rods of three power levels will be employed to obtain radial power variation. The power levels of the rods, compared to the average, will be 1.1, 1.0, and 0.95. The arrangement of the rods to simulate a PWR radial power distribution is shown in Figures 2 and 3.

The axial and radial power distributions of the arrays to be tested correspond conservatively to those that would be found in actual PWR assemblies. The expected axial power distribution is shown in Figure 5.

The heater rods will be supported radially within the test bundle by eight "egg crate" grids of the type shown in Figure 6. Radial positioning of the grid is maintained by springs which contact the housing wall. Positioning of the individual rods is maintained by dimples in the grid. One grid will be located at the bottom of the heated length and one grid will be located at the top. The remaining grids will be spaced at equal intervals between the top and bottom grids. One exception will be made to this grid design. One test run will be performed with a Westinghouse mixing vane grid design.

1.3.2 Thermocouple Location

The heater rod thermocouples are distributed radially and axially throughout the bundle. To install multiple thermocouple attachments on each rod would result in a prohibitive total number of thermocouples required for each test section. The number required is, therefore, reduced by taking advantage of the test bundle symmetry. Radially, the test bundles are two-way symmetric.

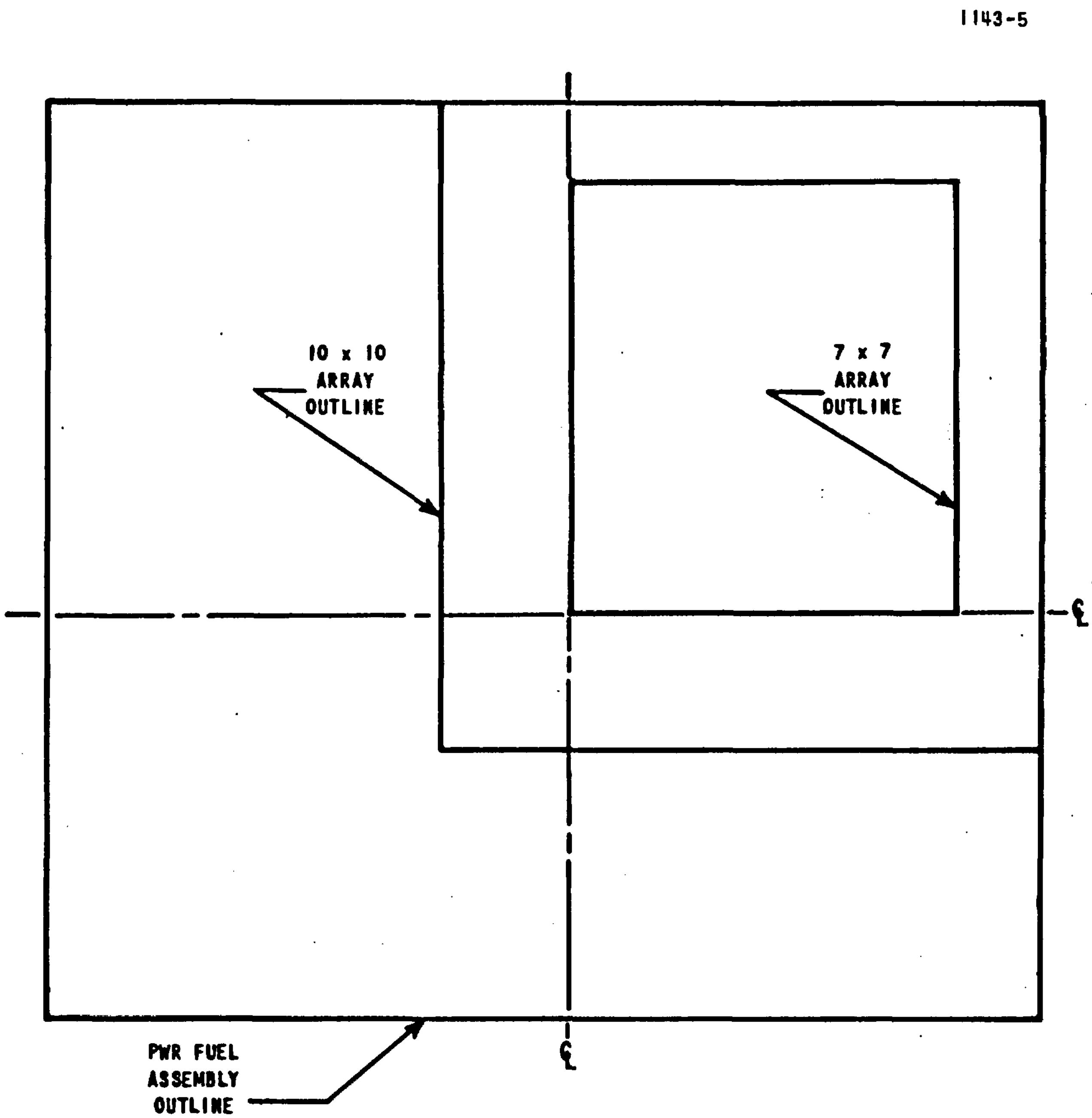

Figure 4. Comparison of PWR Fuel Assembly and FLECHT Test Assembly Array Outlines

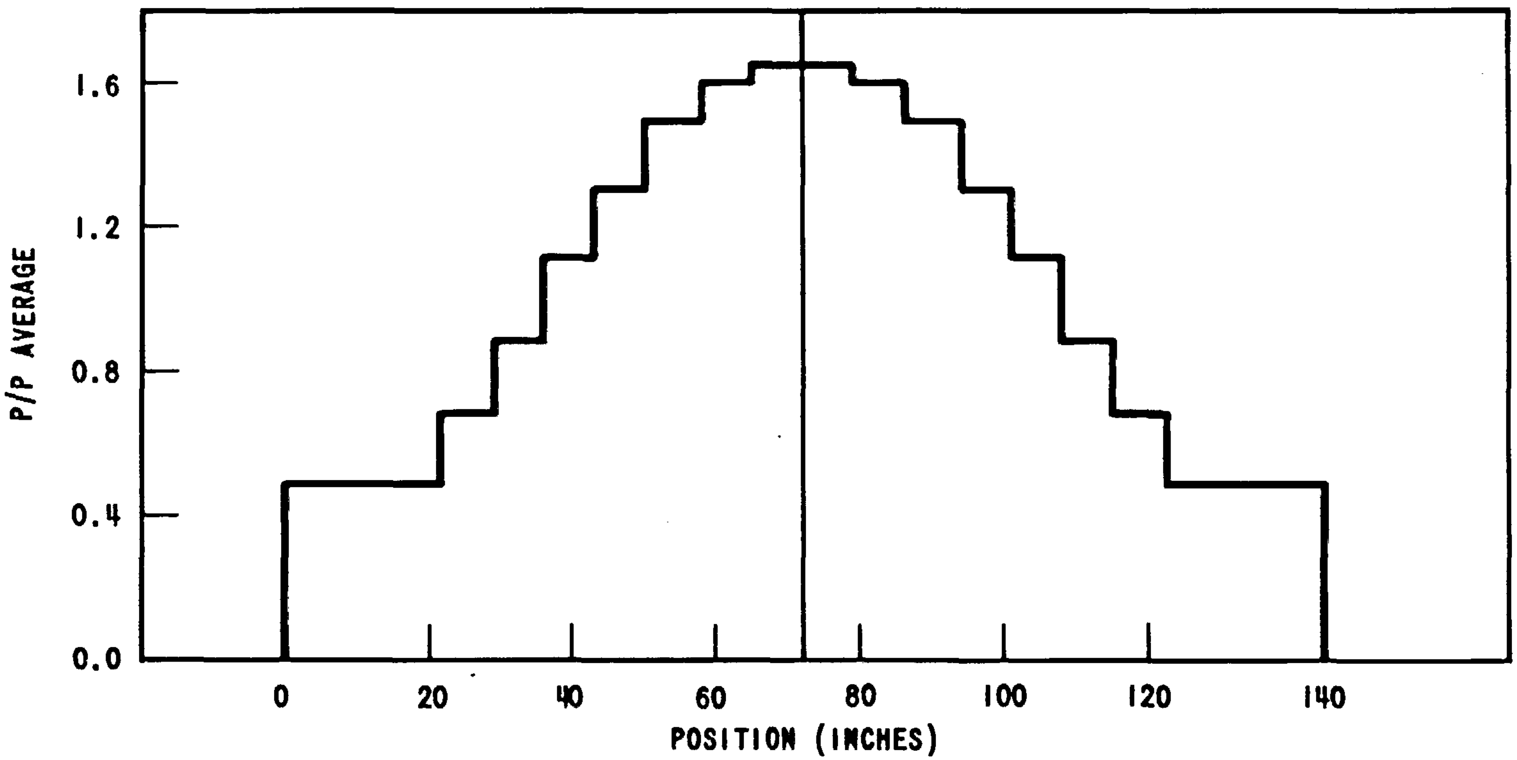

Figure 5. Heater Rod Axial Power Profile

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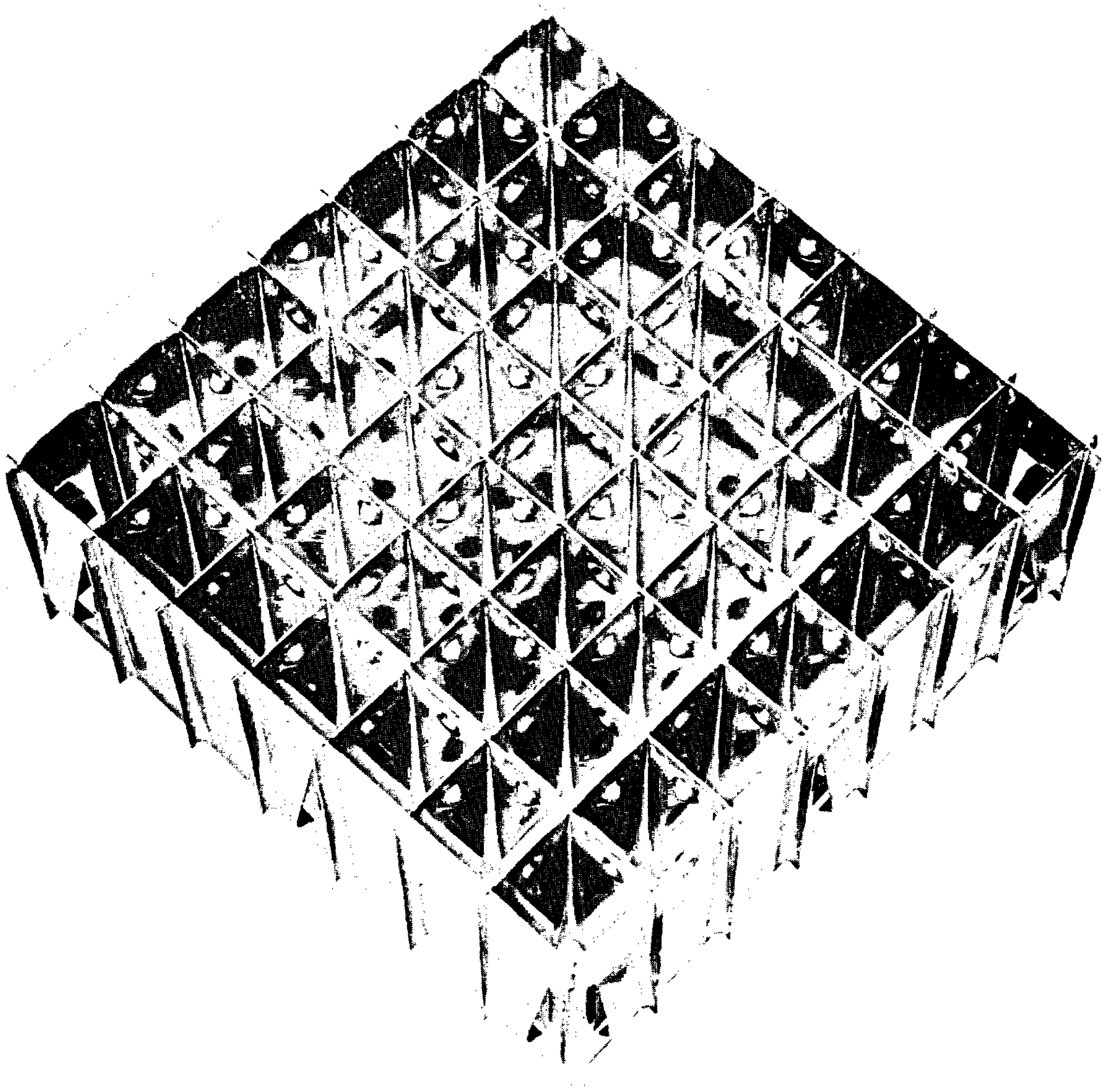


Figure 6. Egg-Crate Grid Used in FLECHT Testing

The number of heater rod thermocouples is further modified by selective placement of the instrumented heater rods. In each test bundle, five of the instrumented heater rods will contain five thermocouples. These five thermocouples will be placed at positions which are two, four, six, eight, and ten feet above the bottom of the heated section of the heater rods. The remaining heater rods will contain three thermocouples at the four, six, and ten feet positions. Figures 7 and 8 show the layout of heater rod thermocouple installation for the 7 x 7 and 10 x 10 test bundles respectively.

One of the three thermocouple rods provides a check on the test bundle symmetry. The number of thermocouples required for each bundle is shown in Table 2.

TABLE 2

THERMOCOUPLES PER ROD BUNDLE

Number of Thermocouples/rod	Number of Rods		Total Number of Thermocouples
	7 x 7 Bundle		
3	11		33
5	5		25
		Total	58
	10 x 10 Bundle		
3	25		75
5	5		25
		Total	100

Other temperature measurements will also be performed within the test bundle. Ten thermocouples will be provided to measure local coolant temperature and six thermocouples will be provided to measure tube wall temperature. These

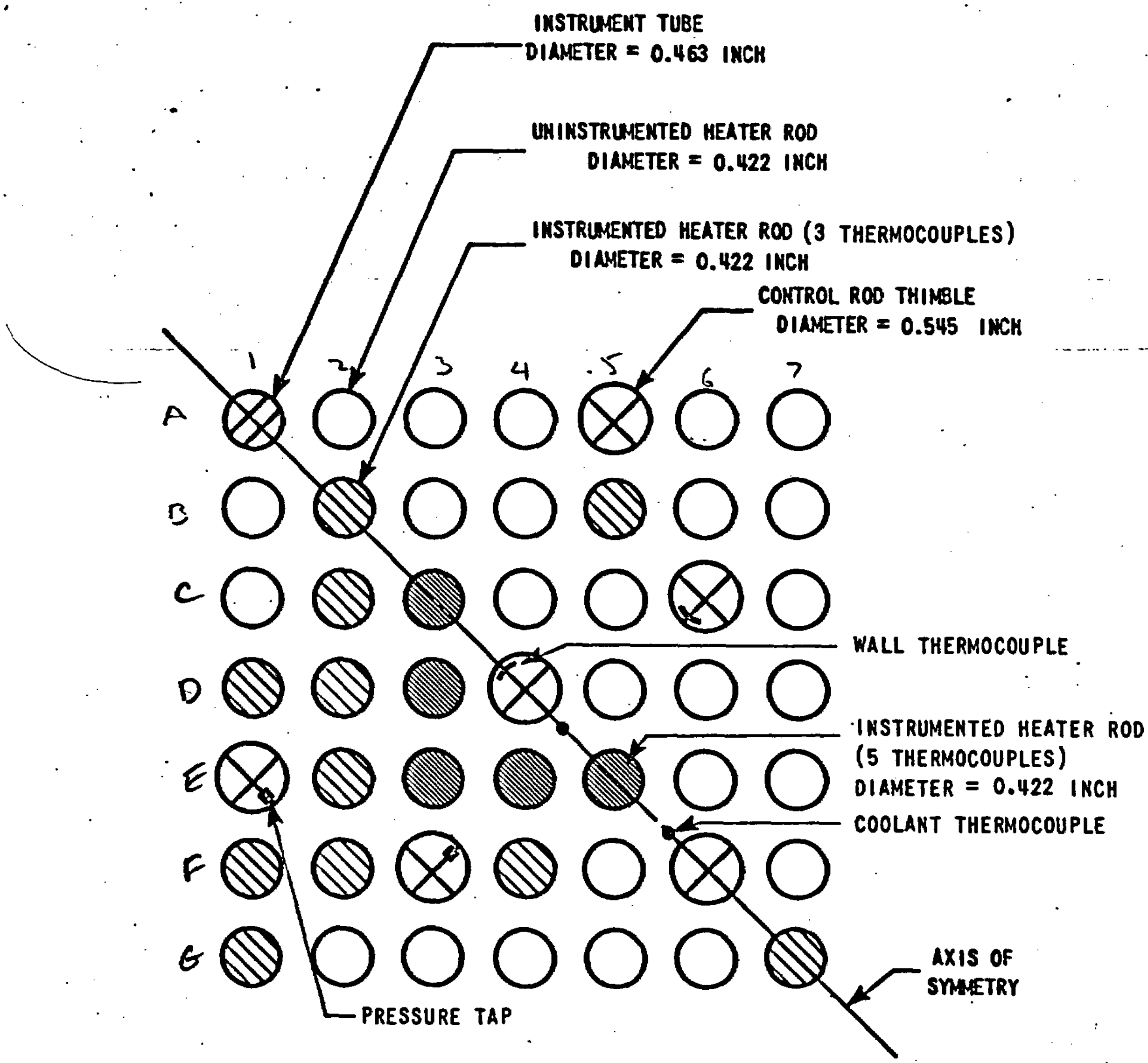


Figure 7. Location of Instrumented Heater Rods in the 7 x 7 Array

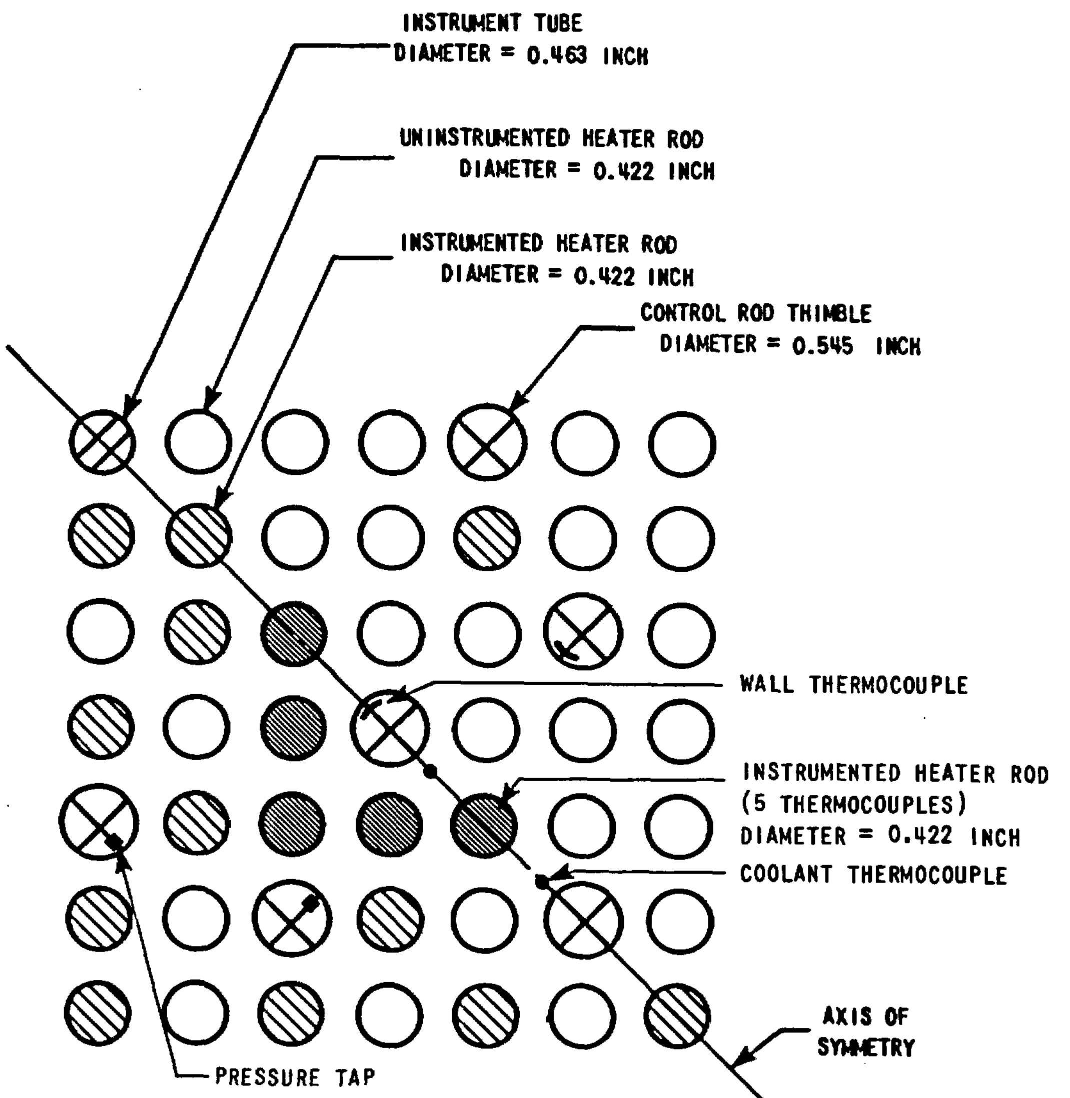


Figure 7. Location of Instrumented Heater Rods in the 7 x 7 Array

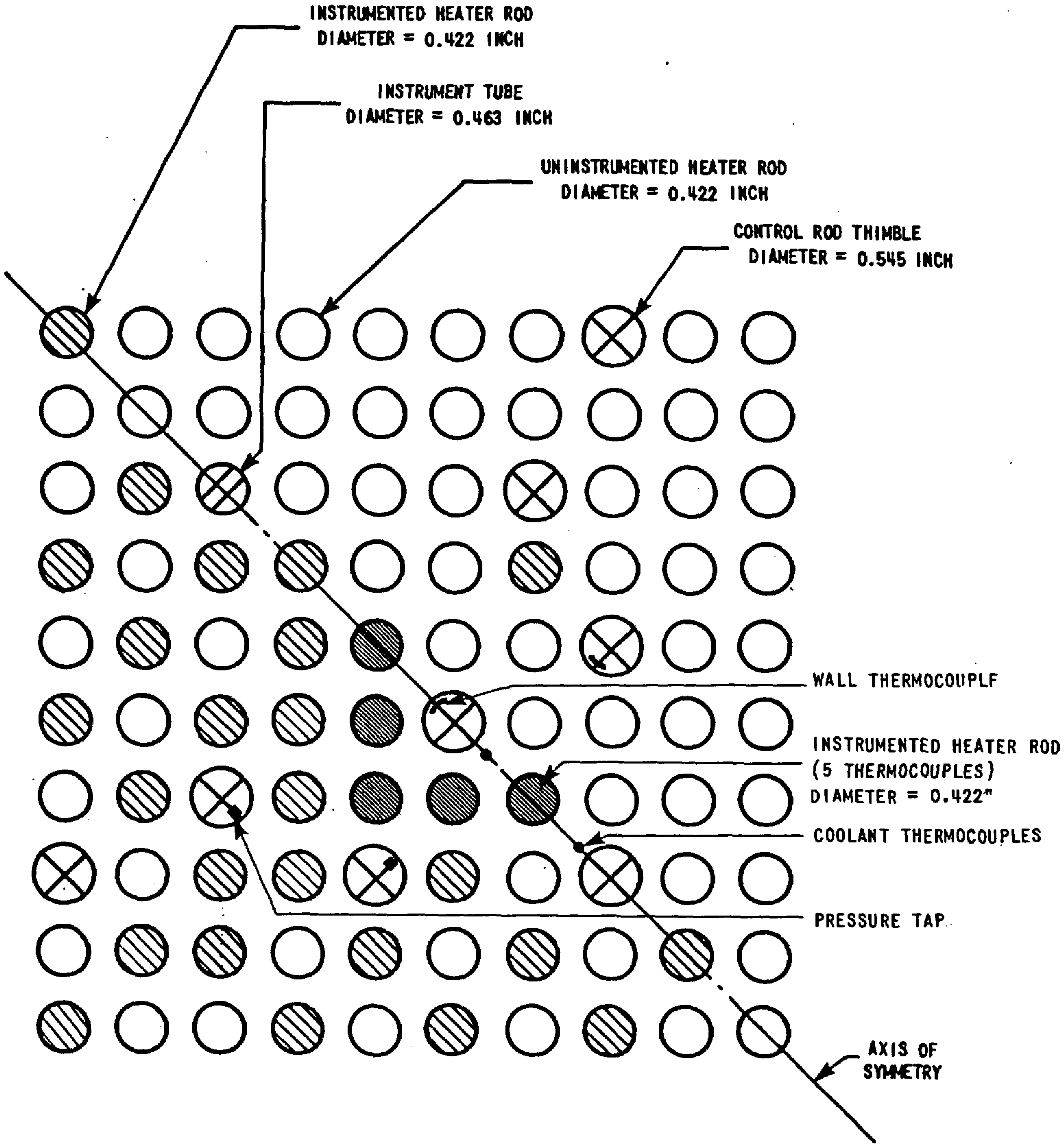


Figure 8. Location of Instrumented Heater Rods in the 10 x 10 Array

will be introduced by way of the control rod guide tubes. Five axial measurements of local coolant temperature and three axial measurements of guide tube wall temperature at two radial locations will be made. Figures 7 and 8 show the radial locations for these measurements. The axial locations will correspond to the three and five thermocouple heater rod sensor locations.

1.3.3 Pressure Transducer Location

Axial and radial local pressure measurements will be made. Five pressure transducers will be distributed axially along the flow housing wall. The radial measurements will be obtained by mounting pressure taps within two of the control rod guide tubes as shown in Figures 7 and 8. The axial location of the guide tube taps will correspond to the elevation of the flow housing tap which is closest to the bottom of the heated length of the heater rods.

SECTION 2

TEST LOOP

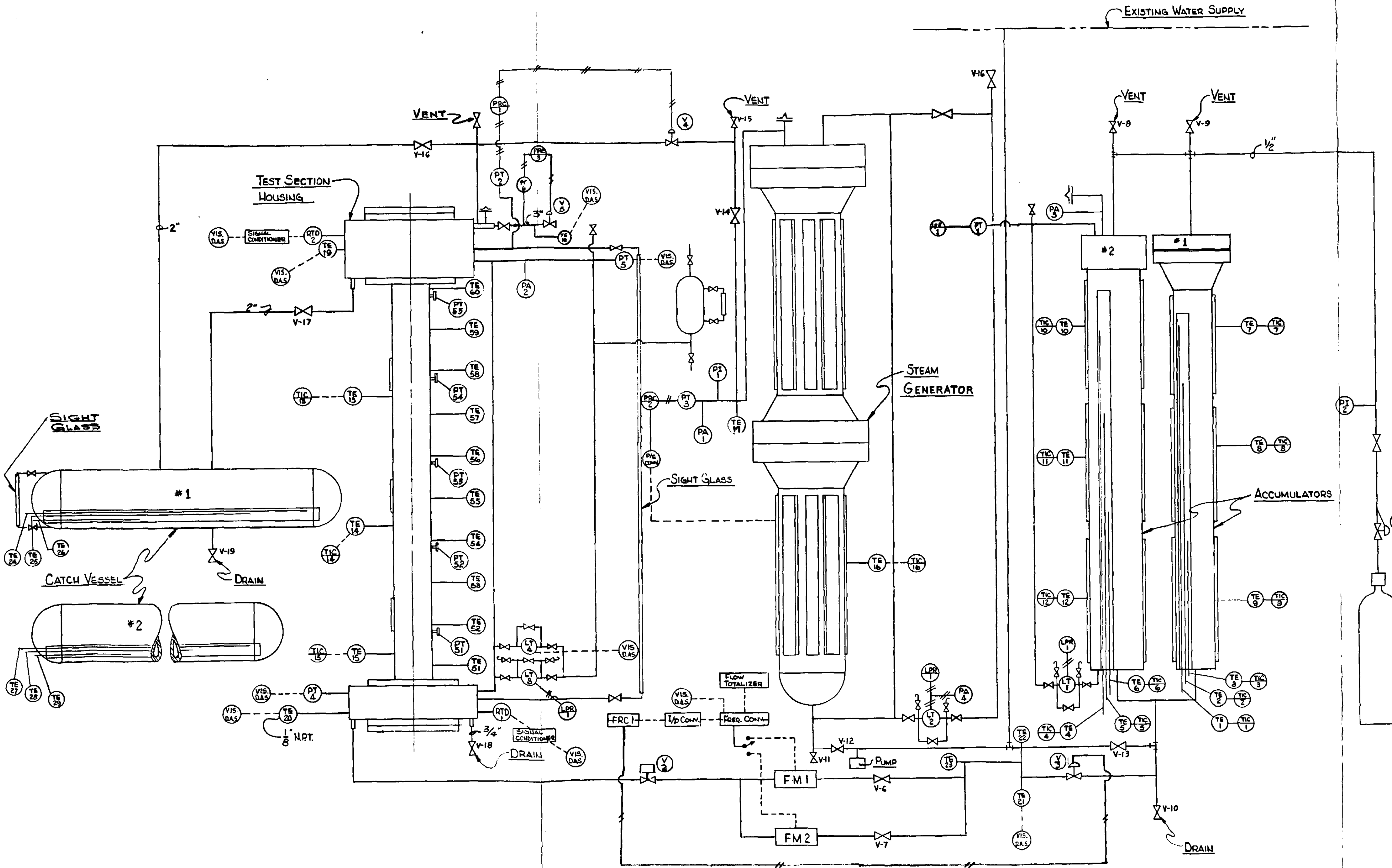
2.1 FACILITY

The flowsheet of the facility is shown in Figure 9. The facility is a once-through system consisting of a flow housing for the test bundle, a coolant accumulator, a coolant catch vessel, a steam boiler for back-pressure regulation, a gas supply system for coolant injection and the required piping and valves. The flow housing is also the pressure containing number. A photograph of the facility during construction is shown in Figure 10.

The flow of gas to the coolant accumulator is controlled by a Mity-Mite type pressure regulator, V-1. The coolant flow enters the test section housing through a manifold to assure proper flow distribution. The flow is regulated by a pneumatically operated control valve, V-3. Valve V-3 is controlled by the output from a turbine meter, monitoring the coolant flow. The required test section housing pressure, previous to the injection of coolant, is established by throttling the steam pressure in the boiler by means of a control valve, V-4. The test section housing pressure during the experimental run is regulated by means of the pneumatically operated control valve, V-5, releasing the steam pressure to the atmosphere. The water "burped out" of the test section is collected in the plenum chamber and is prevented from falling back into the rod bundle. The water is drained from the plenum, collected and measured in the catch vessel.

To simulate a pressure build up in the test section housing during the experimental run a valve is installed in the pipeline between the test section housing and the control valve, V-5.

Separate square housings are required for the 49 and 100 rod test bundles while the plenum chamber and the manifold are flanged and used alternately on



LEGEND:

TE ~ Temp. Element
TIC ~ Temp. Indicator Controller
PT ~ Press. Transducer
PI ~ Press. Indicator
LT ~ Level Transmitter
LPR ~ Level Press. Recorder
PA ~ Press. Alarm
RTD ~ Resistance Temp. Detector
FRC ~ Flow Recorder Controller
PRC ~ Press. Recorder Controller
Vis. D.A.S. ~ Visicorder - Digital Aquisition System
FM ~ Flow Meter

Figure 9. FLECHT Test Facility Flow Sheet (EDSK 341638D)

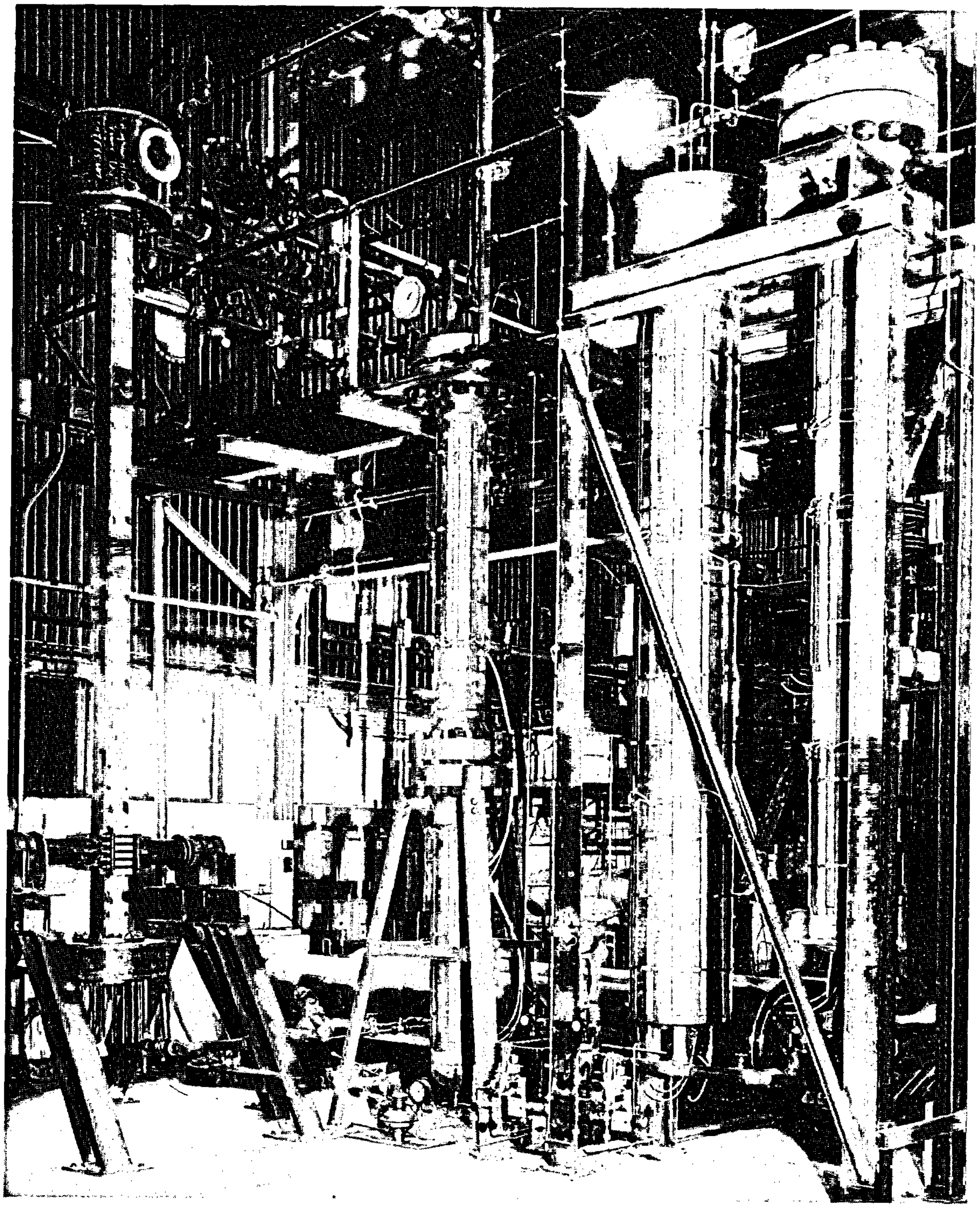


Figure 10. FLECHT Test Facility During Construction

either of the two housings. The square units are designed for 100 psig and 800°F and fabricated from carbon steel.

The thickness of the walls of the two square housings is 0.70 inch. The thick walls provide heat storage, thus minimizing rapid cool-down of the walls during the experimental run. These walls are supplied with clamped-on heaters with a capacity of 49 kw and 60 kw for the 49 and 100 rod test housings, respectively, to raise their temperature to the order of 600°F to 800°F at the start of the experimental run. The test section housings are insulated with a two-inch thick layer of mineral wool to limit heat losses to the surroundings to approximately 2 kw.

The internal dimensions of the two housings are 4.200 inches ± 0.020 inch and 5.889 inches ± 0.020 inch with an internal surface finish of 125 micro-inches.

The 100 rod flow housing is designed with three rectangular quartz glass ports for viewing and photographic study. The plenum chamber is supplied with one circular quartz glass port.

The test rod penetration seals, are an O-ring type and flanged onto the plenum chamber and the manifold. The O-rings, made of Ethylene Propylene Rubber, have been tested in a facility with steam at 200 psi and 500°F. For these tests, rods were moved up and down approximately 50 times with the O-rings stationary, simulating the thermal expansion of the test rods. No steam leakage was observed.

The test section housings are supported on a frame and operated in a vertical position. For loading and unloading purposes the test housings are rotated around a central support axis to a horizontal position.

The method of power control for the heater rods is shown on Figure 11. Power is supplied by a 1500 kva transformer through a 1600 amp, 460 volt circuit breaker. Power is distributed to three SCR power control units through individual 1000 amp circuit breakers. The SCR's in the power control units are rated at 1200 amps at 460 volts. The secondary of the supply transformer is star connected with a neutral. The nichrome heater rod tests require 440 volts and the molybdenum heater rods require less than 277 volts.

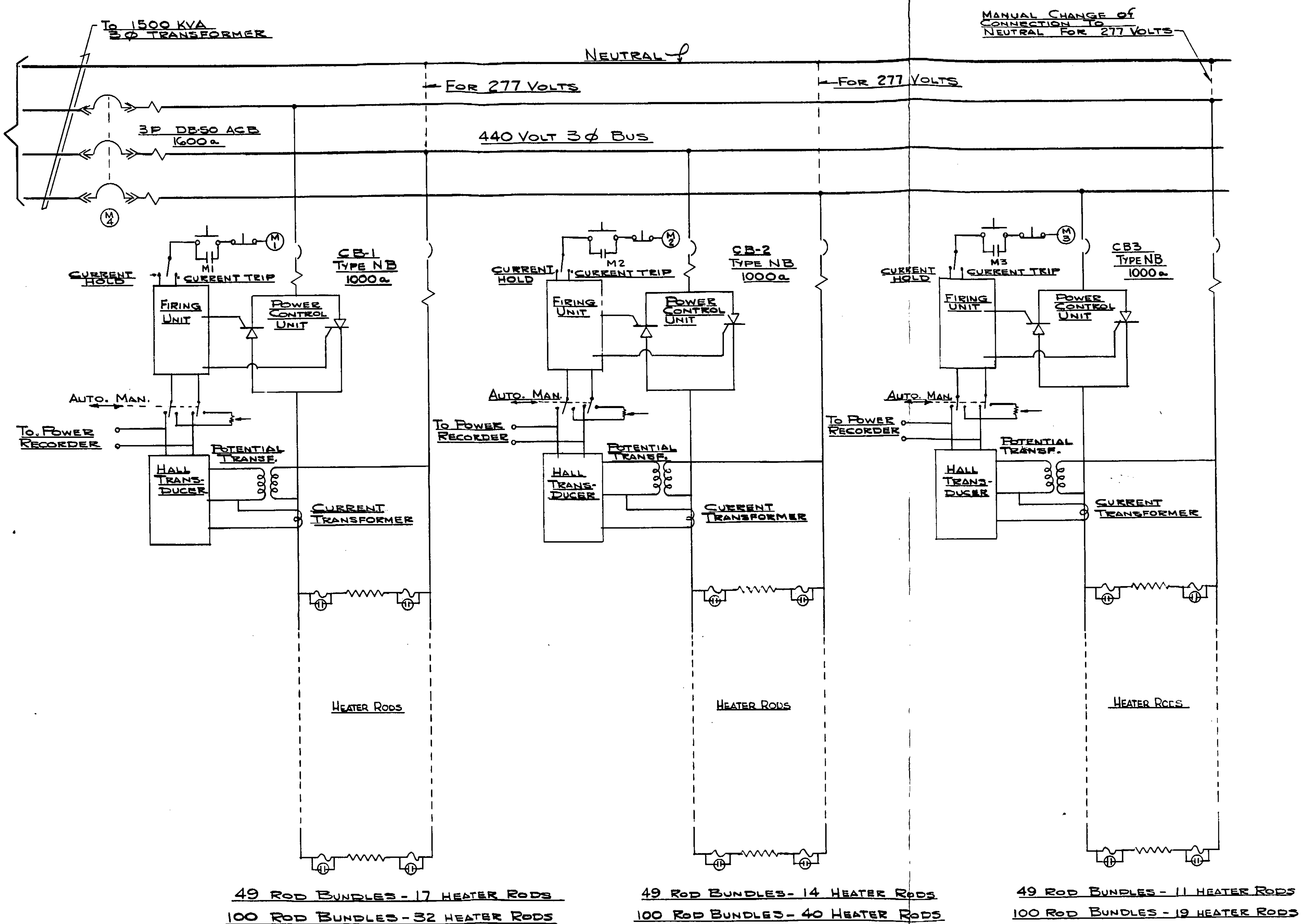


Figure 11. FLECHT Heater Rod Power Schematic (EDSK 329165)

In order to simulate the estimated decay heat generated by a shutdown reactor, the three SCR power control units can be biased either with three manually adjustable potentiometers or automatically through a curve follower programmer. The programmer consists of an instrument with a pen following the decay heat curve drawn on electrostatic paper.

The pen of the programmer mechanically drives three potentiometers to bias each power control unit. The potentiometers are offset in order to effect the required radial power profile.

An undervoltage relay in the control circuit trips the power to the heater rods in the event that the voltage to the instrumentation and control circuits is lost. Each heater rod is protected against burnout by individual fast acting fuses in both sides of the line. If the coolant flow falls below a specified value, power to the test rods is turned off manually.

2.2 INSTRUMENTATION

The instrumentation of the facility is shown in Figure 9 and itemized in Table 3, Facility Instrumentation List. The temperature of the water in the accumulator is monitored by an immersion type thermocouple which feeds a time-proportional controller TIC-1. This controller regulates the power input to the externally clamped-on heaters. A thermcouple, TE-2, located on the clamped-on heaters protects the accumulator wall against excessive temperature. A pressure switch, PA-3, trips the heater elements on low and high accumulator pressure. Nitrogen gas maintains the accumulator at constant pressure. A pressure transmitter, PT-1, monitors and feeds a recorder that records the accumulator pressure. The level in the accumulator is measured by a D/P-cell, level transmitter, LT-1, and recorded.

The steam generator is heated with externally clamped-on heaters having a total capacity of about 27 kw. Pressure transducer PT-3 monitors the steam pressure in the generator and the pressure is recorded on PRC-2, which also acts as the time-proportional control for the clamped-on heaters. The steam generator is protected against excessive temperature by a thermocouple, TE-16, located on the clamped-on heaters. The water level in the steam generator is

TABLE 3

FACILITY INSTRUMENTATION LIST

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TIC-1	Temperature Indicating Controller, Honeywell Model R-7161B, time proportioning with reset	Controls accumulator #1 top zone heater	TE-1	0-400°F	0-400	± 1% of full scale
TIC-2	Same as TIC-1	Controls accumulator #1 mid-zone heater	TE-2	0-400°F	0-400	± 1% of full scale
TIC-3	Temperature Indicating Controller, ECS Model 909, time proportioning with reset	Controls accumulator #1 bottom zone heater	TE-3	0-800°F	0-800	1% of full scale
TIC-4	Same as TIC-1	Controls accumulator #2 top zone heater	TE-4	0-400°F	0-400	1% of full scale
TIC-5	Same as TIC-1	Controls accumulator #2 mid-zone heater	TE-5	0-400°F	0-400	1% of full scale
TIC-6	Same as TIC-1	Controls accumulator #2 bottom zone heater	TE-6	0-400°F	0-400	1% of full scale
TIC-7	Temperature Indicating Controller, Honeywell Model #R7161C	Over temperature protection of accumulator #1 top zone, trips at 1000°F	TE-7	0-1200°F	0-1200	1% of full scale

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TIC-8	Same as TIC-7	Over temperature protection of accumulator #1 mid-zone, trips at 1000°F	TE-8	0-1200°F	0-1200	1% of full scale
TIC-9	Temperature Indicating Controller, ECS Model 905, on-off control	Over temperature protection of accumulator #1 bottom zone, trips at 1000°F	TE-9	0-1600°F	0-1600	1% of full scale
TIC-10	Same as TIC-9	Over temperature protection of accumulator #2 top zone, trips at 1000°F	TE-10	0-1600°F	0-1600	1% of full scale
TIC-11	Same as TIC-9	Over temperature protection of accumulator #2 top zone, trips at 1000°F	TE-11	0-1600°F	0-1600	1% of full scale
TIC-12	Same as TIC-9	Over temperature protection of accumulator #2 bottom zone, trips at 1000°F	TE-12	0-1600°F	0-1600	1% of full scale
TIC-13	Same as TIC-3	Controls flow housing top zone temperature	TE-13	0-1200°F	0-1200	1% of full scale

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TIC-14	Same as TIC-3	Controls flow housing mid-zone temperature	TE-14	0-1200°F	0-1200	1% of full scale
TIC-15	Same as TIC-3	Controls flow housing bottom zone temperature	TE-15	0-1200°F	0-1200	1% of full scale
TIC-16	Same as TIC-9	Over temperature protection steam generator, trips at 1000°F	TE-16	0-1600°F	0-1600	1% of full scale
TE-1	Iron-constantan thermocouple	Accumulator #1 water control top zone output to TIC-1		1400°F		1/2% of reading
TE-2	Iron-constantan thermocouple	Accumulator #1 water control mid-zone output to TIC-2		1400°F		1/2% of reading
TE-3	Iron-constantan thermocouple	Accumulator #1 water control bottom zone output to TIC-3		1400°F		1/2% of reading
TE-4	Iron-constantan thermocouple	Accumulator #2 water control top zone output to TIC-4		1400°F		1/2% of reading
TE-5	Iron-constantan thermocouple	Accumulator #2 water control mid-zone output to TIC-5		1400°F		1/2% of reading

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TE-6	Iron-constantan thermocouple	Accumulator #2 water control bottom zone output to TIC-6		1400°F		1/2% of reading
TE-7	Iron-constantan thermocouple	Over temperature protection accumulator #1 top zone output to TIC-7		1400°F		1/2% of reading
TE-8	Iron-constantan thermocouple	Over temperature protection accumulator #1 mid-zone output to TIC-8		1400°F		1/2% of reading
TE-9	Iron-constantan thermocouple	Over temperature protection accumulator #1 bottom zone output to TIC-9		1400°F		1/2% of reading
TE-10	Iron-constantan thermocouple	Over temperature protection accumulator #2 top zone output to TIC-10		1400°F		1/2% of reading
TE-11	Iron-constantan thermocouple	Over temperature protection accumulator #2 mid-zone output to TIC-11		1400°F		1/2% of reading

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TE-12	Iron-constantan thermocouple	Over temperature protection accumulator #2 bottom zone output to TIC-12		1400°F		1/2% of reading
TE-13	Iron-constantan thermocouple	Flow housing wall temperature control top zone output to TIC-13		1400°F		1/2% of reading
TE-14	Iron-constantan	Flow housing wall temperature control mid-zone output to TIC-14		1400°F		1/2% of reading
TE-15	Iron-constantan thermocouple	Flow housing wall temperature control bottom zone output to TIC-15		1400°F		1/2% of reading
TE-16	Iron-constantan thermocouple	Over temperature protection steam generator output to TIC-16		1400°F		1/2% of reading
TE-17	Copper-constantan thermocouple	Monitors steam temperature output to D.A.S./Vis.		750°F		3/8% of reading
TE-18	Copper-constantan	Monitors steam input to flow housing output to D.A.S./Vis.		750°F		3/8% of reading

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TE-19	Copper-constantan thermocouple	Monitors temperature upper plenum output to D.A.S./Vis.		750°F		3/8% of reading
TE-20	Copper-constantan thermocouple	Monitors temperature lower plenum output to D.A.S./Vis.		750°F		3/8% of reading
TE-21	Copper-constantan thermocouple	Monitors water temperature between accumulator and flow housing output to D.A.S./Vis.		750°F		3/8% of reading
TE-22	Copper-constantan thermocouple	Same as TE-21		750°F		3/8% of reading
TE-23	Copper-constantan thermocouple	Same as TE-21		750°F		3/8% of reading
TE-24	Iron-constantan thermocouple	Monitors #1 catch vessel temperature output to D.A.S.		1400°F		1/2% of reading
TE-25	Iron-constantan thermocouple	Same as TE-24		1400°F		1/2% of reading
TE-26	Iron-constantan thermocouple	Same as TE-24		1400°F		1/2% of reading

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
TE-27	Iron-constantan thermocouple	Monitors #2 catch vessel temperature output to D.A.S.		1400°F		1/2% of reading
TE-28	Iron-constantan thermocouple	Same as TE-27		1400°F		1/2% of reading
TE-29	Iron-constantan thermocouple	Same as TE-27		1400°F		1/2% of reading
TE-51 thru TE-60	Chromel-Alumel Thermocouple premium grade	Flow housing wall temperature		2000°F		± 3/8% of reading
PI-1	Pressure Indicator, 8-1/2" dial, Ashcroft Model 1082	Steam generator pressure		2000 psig	2000 psig	± 1/4% of full scale
PI-2	Pressure Indicator, 8-1/2" dial, Ashcroft Model 1082	Accumulator pressure		2000 psig	2000 psig	± 1/4% of full scale
PRC-3	Pressure Recorder Controller Foxboro Model 40-RA-4 proportional band plus reset	Regulate back pressure on test section housing	PT-6	0-100%	0-100%	± 1/4% of full scale

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
PT-4	Pressure Transducer, Tabor Model 206	Flow housing inlet plenum pressure output to visicorder/DAS		0-300 psig input for low pressure runs; 3 mv/v/psi output	0-300 psig	± 1/4% of full scale
PT-5	Pressure Transducer, Tabor Model 206	Flow housing outlet plenum pressure output to visicorder/DAS		0-300 psig input, 3-15 psi output	0-150 psig	± 1/4% of full scale
PRC-1	Pressure Recorder Controller, Foxboro Model 40-RA-4, proportional band plus reset	Controls steam pressure in flow housing	PT-2	0-100% 3-15 psi input	0-100%	Sensitivity .01% of full psig scale
PRC-2	Pressure Recorder Controller, Foxboro Model 40-RA-4, proportional band plus reset	Controls steam generator heaters	PT-3	0-100% 3-15 input	0-100%	Sensitivity .01% of full scale
PA-1	Pressure Alarm, Meletron Model 312-6SS-65A	Trips steam generator heaters and actuated alarm at 2000 psig steam generator pressure		50-2500 psig	0-2000 psig	± 1/2%

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
PA-2	Pressure Alarm, Meletron Model 312-6SS-65A	Trips flow housing heaters and steam generator heaters at flow housing design pressure		50-2500 psig	0-100 psi	± 1/2%
PT-6	Pressure Transmitter, Foxboro Model #44	Flow housing back pressure		0-300 psig input for low pressure runs	0-150 psig	± 1/4% of full scale
LT-3	Level Transmitter, Foxboro Model 13A	Monitors water level of flow housing output to LPR-1		0-200" of water, 3-15 output	0-180-5" H_2O	± .5%
LT-4	Level Transducer, Statham Model PM 385	Monitors water level of flow housing output to LPR-1		± 10 psid input, 3 mv/v/psi output	± 10 psid	± 3/4% of full scale
FM-1	Flowmeter, Potter Model 5000 turbine 1/2 inch size	Measures inlet flow output to frequency converter		1.25 to 9.5 input, 3160 pulses per gallon output		± 1/4% of full scale

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
PT-1	Pressure Transmitter, Foxboro Model 44	Accumulator pressure output recorded by LPR-1		0-2000 psig input: 3-15 psi output	0-2000	± 3/4%
PT-2	Pressure Transmitter, Foxboro Model 44	Flow housing steam pressure output to PRC-1		Input-200 for low pressure runs, 0-1500 for high pressure runs; 3-15 psi output	0-200 psig	± 3/4%
PT-3	Pressure Transmitter, Foxboro Model 44	Steam supply pressure output to PRC-2		0-2000 psig input, 3-15 psi output	0-2000 psig	± 3/4%
PA-3	Pressure Alarm, Meletron Model 312-6SS-65A	Trips accumulator heaters at 2000 psig accumulator pressure		65-3200 psig	2000 psig	± 1/2%
PA-4	Pressure Alarm, Meletron Model 424	Trips steam generator heaters on low steam generator water level	LT-2	0.2-15 psi	4 psi	± 1/2%

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
P/E Conv.	Pneumatic to Electric Converter Foxboro Model 224-EU-10J-89	Converts pneumatic output of PRC-2 to proportional electrical signal for relay control of steam generator heaters		3-15 psi input, on-off output		
LPR-1	Pneumatic Recorder, Four Pen, Fischer-Porter Model 1600	Records pressure in accumulator and records level of accumulator steam generator and flow housing	PT-1 LT-1 LT-2 LT-3	0-100%	0-100%	
LT-1	Level Transmitter, Foxboro Model 13A	Monitors water level of accumulator output to LPR-1		0-205" of water input, 3-15 psi output	173"	± .5%
LT-2	Level Transmitter, Foxboro Model 13A	Monitors water level of steam generator output to LPR-1 and PA-4		0-205" of water input, 3-15 psi output, 0-81" of water, 3-15 psi output	148" H_2O	± .5%

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
FM-2	Flowmeter, Potter Model Turbine, 1 inch size	Measures inlet flow output to frequency converter		4 to 60 gpm input, 500 pulses per gallon output		± 1/4% of full scale
FREQ. CONV.	Frequency Converter, Potter Model 581	Converts frequency signal to proportional output current - 10 to 50 ma. dc. output to FRC-1	FM-1/ FM-2	0-4 KC	10-50 MA	± 0.1% of full scale
Flow Totalizer	Digital Totalizer, Potter Model 522	Totalizes the flow	FM-1/ FM-2	100 million count capacity		± count
I/P Conv.	Current to Pneumatic Converter Foxboro Model M69TA-24	Accepts signal from frequency converter and sends proportional air signal to FRC-1	FM-1/ FM-2	10-50 ma. dc. input, 3-15 psi output	3-15 psi	± 1/2% of full scale
FRC-1	Flow Recorder Controller, Foxboro Model 5412-TSF, proportional band plus reset	Controls inlet flow thru V-3	FM-1/ FM-2	0-100% scale 3-15 psi input	0-100%	± 1/2% of
JR-1	Power Recorder, Texas Inst. Model FLO3W6D, 3 pen	Records outputs of (3) SCR power control units	Hall Generator	0-10 Millivolts input	0-10 M.V.	± 1/4% of full scale

TABLE 3

FACILITY INSTRUMENTATION LIST (Contd)

DESIGNATION	DESCRIPTION	FUNCTION	SENSOR	RANGE	CALIB.°F	ACCURACY
KS	Timer, Industrial Timer Corp. Model GTD-30M	Opens V-2 at test initiation, closes V-2 at end of pre-set time		0-30 min.		± 1%
RTD-1	Resistance Temperature Detector, Rosemont Engrg. Model 414L	Monitors inlet water temperature, output to visicorder/DAS		0-1000°F	0-1000°F	± 0.6°F
RTD-2	Resistance Temperature Detector, Rosemont Engrg. Model 414L	Monitors outlet water temperature, output visicorder/DAS		0-1000°F	0-1000°F	± 0.6°F
	Thermocouple Reference Junction - J. Kaye Model 2700, Type K, 5 units - 24 Channels each	References heater rod thermocouples to 150°F		150°F		± 0.2°F

measured by a D/P-cell type level transmitter and recorded on LPR-1. PA-4 trips the steam generator heaters on low water level.

Pressure difference between the inlet and the outlet of the test section housing and the water level in the test section housing, are measured with two pressure differential cells, LT-3 and LT-4. The water level in the test section housing is also monitored locally using a sight glass. Resistance thermometers and thermocouples at the inlet and outlet to the test section housing monitor the coolant temperature.

The pressure in the test section housing is monitored and controlled. Valve V-4 controls the pressure of the generated steam to the flow housing, and valve V-5 regulates the back-pressure on the test section housing by relieving the pressure to the atmosphere during the experimental run.

To monitor the wide range of coolant flows to the flow housing, two turbine meters are used. The output from the turbine meters is recorded and fed to the controller FRC-1; the output of FRC-1 proportionally positions a pneumatically operated control valve, V-3. Injection of coolant water to the test section housing is initiated manually by a switch opening the solenoid valve V-2. The coolant flow can be terminated automatically or manually.

The flow housing clamped-on heaters are on/off controlled by thermocouples monitoring the wall temperature of the flow housing.

Pressure transducers are to be installed to measure the axial pressure variations in the 49 and 100 rod flow housings. Statham bi-directional differential pressure transducers are used for these measurements. The signals from the pressure transducers are recorded on both the digital acquisition system and the visicorder.

The water collected in the catch vessel is measured with a level indicator.

SECTION 3

TEST PROCEDURE

3.1 METHOD OF RUNNING TEST

The experimental facility is to be operated as a once-through system. The accumulator is filled with demineralized water and pressurized with gas to a pressure of about 500 psi above the pressure in the test section housing. The accumulator is maintained at a constant pressure during the experimental run. The required coolant temperature is established by means of the externally clamped-on heaters.

A small amount of water is allowed to enter the test section housing to a level just below the heated length of the test rods.

The walls of the test section housing are heated to a temperature in the range 600°F to 800°F and then pressurized with steam from the boiler to the required pressure.

Power is then applied to the test rods and the rods are allowed to heat up. It is anticipated that the rods with a nichrome heater element will be heated at constant power while the rods with the molybdenum heater elements will be heated at constant amperage. However, the rate of heating may be varied as desirable. When the temperature in a designated rod reaches a pre-set value, the solenoid valve V-2, is opened by means of a manually operated switch and the coolant is injected into the test section housing at the desired rate.

Coolant drainage or trace heating or a combination of both will be utilized to assure that the coolant water in the test section housing and the pipe line between the test section housing and the accumulator is at the correct temperature at the time water injection is initiated.

On initiation of coolant injection, decay of test rod power at a programmed rate corresponding to the reactor decay heat is automatically started. The programmed rate of decay is shown in Figure 12, Reactor Power Decay Curve. The control valve V-5 regulates the test housing pressure by releasing steam to the atmosphere. The "burped out" water, after partial separation, is collected in the catch vessel and measured.

The injection of water can be terminated automatically or manually.

3.2 CALIBRATION PROCEDURE

The heater rod thermocouples are ordered with the requirement that before shipment they be annealed so as to conform to within ± 3/8 percent of the standard emf-millivolt curve. The thermocouples will be wired to a Jos. Kaye Model 2700 reference junction compensator. The reference temperature is 150°F ± 0.1°F. Most of the thermocouples will be scanned by a digital data acquisition system at a rate of 30 channels per second. The digital system is rated at 0.03 percent accuracy. After digitizing the signal values will be recorded in BCD form on magnetic tape and later reduced to engineering units and plotted by an off-line CDC 6600 digital computer. The remaining thermocouples will be recorded by a light beam oscillograph at 1-1/4 percent basic accuracy. The total accuracy will depend on knowing the change in resistance of that portion of the thermocouple wire in the heater rod, due to the temperature gradient of the heater rod.

The copper/constantan thermocouples used to measure inlet coolant temperature will be calibrated at the ice point and boiling point of water with a calibrated thermometer.

The outlet coolant copper/constantan thermocouple, the local coolant chromel/alumel thermocouples and the flow housing wall temperature chromel/alumel thermocouples will be calibrated in a thermocouple calibration furnace. The thermocouples will be checked at five temperatures using an Eppley standard cell, a Leeds and Northrup K-3 potentiometer and a platinum-10 percent platinum-rhodium thermocouple. These calibration items are traceable to the National Bureau of Standards through the Westinghouse Research Laboratory Standards Lab.

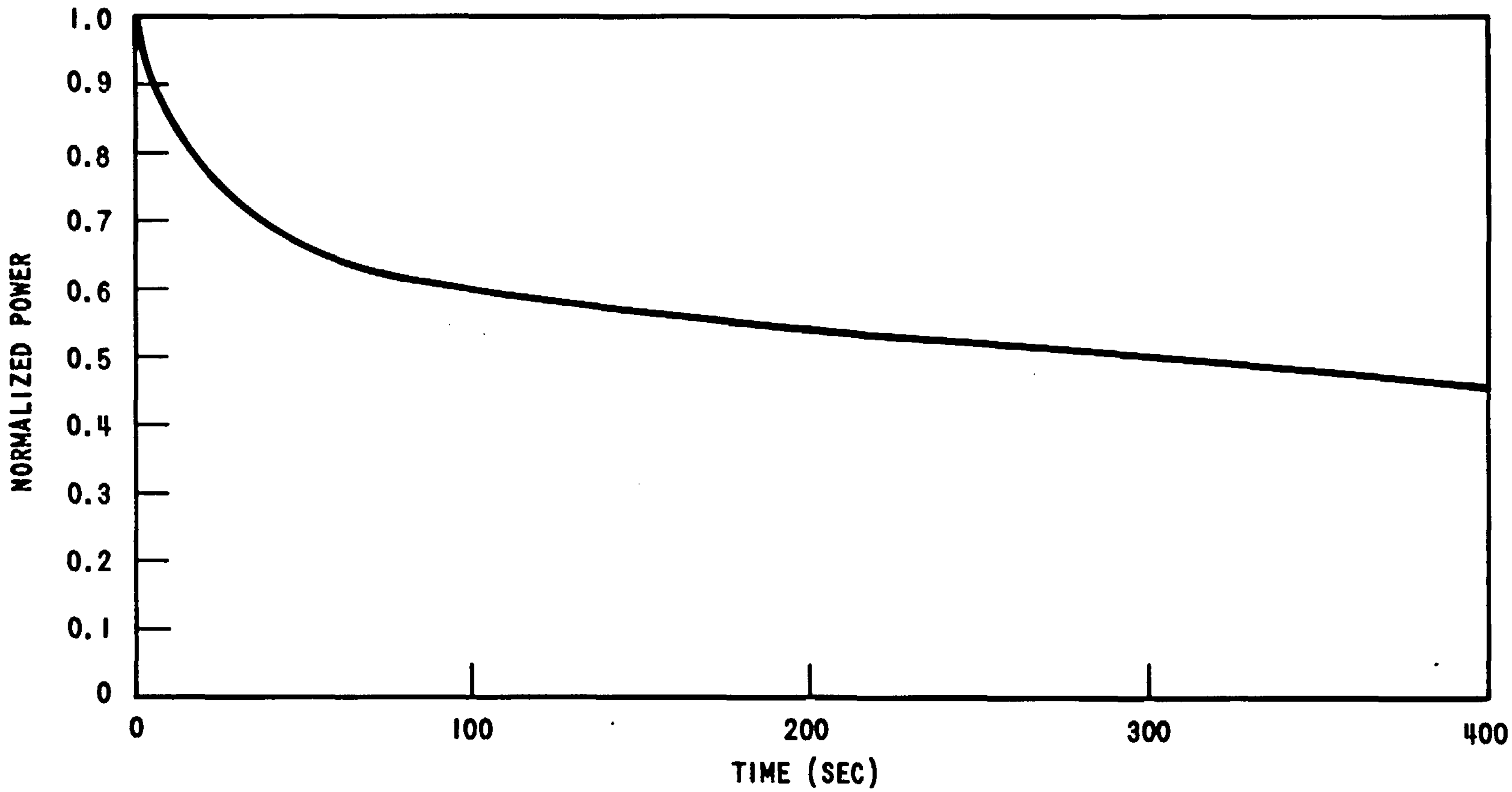


Figure 12. Reactor Power Decay Curve

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The pressure cells will be calibrated at 5 percent, 20 percent, 50 percent, 80 percent, and 95 percent of the appropriate pressure range using an Ashcroft dead weight tester accurate to ± 0.1 percent.

Two Potters turbine flowmeters, calibrated at 70°F, are used to measure coolant flow rates. A factory-supplied correction factor is applied to the flowmeter readings when the coolant temperatures are above 70°F to compensate for the slight thermal expansion of the flowmeters. The correction factor is less than 0.5 percent for the maximum temperature of 200°F.

The power into the heater rods will be supplied by three controllers according to the radial power density required. The controllers will be supplied with a current regulator pre-amp to allow 1 percent accuracy of the set-point from 20 percent to 100 percent of the range. The set-point can be set to supply constant current or can be varied to program a power decay curve.

The power of each of the radial sections of the heater rod bundle will be detected by a potential and a current transformer. The transformer outputs will be multiplied by three Hall effect devices and continuously recorded on three null balance recorders. The three power supply units will be calibrated by the manufacturers. Overall accuracy should be within ± 1-1/2 percent.

SECTION 4

ERROR ANALYSIS

The data obtained from FLECHT testing will be used to determine local heat transfer coefficients. By definition, the heat transfer coefficient is a function of heat flux, surface temperature and local fluid temperature:

$$h = \frac{q''_{surface}}{T_{wall} - T_{fluid}}$$

Therefore, the determination of the heat transfer coefficient is subject to error due to errors generated in the measurement or calculation of these three parameters.

The calculation of the heat transfer coefficient is determined by a computer code (DATAR) which performs a transient conduction calculation based on a known temperature on the inside surface of the rod cladding. The code calculates rod surface temperature, surface heat flux and heat transfer coefficient.

The local fluid temperature is assumed to be equal to the saturation temperature. The validity of this assumption will be checked using direct measurements of coolant temperature taken during the test.

Errors in the calculation of the local heat transfer coefficient are a result of uncertainties in the following factors:

1. Heater rod geometry.
2. Physical properties.
3. Thermocouple measurement.
4. Power measurement.
5. Assumptions incorporated in the transient conduction calculation.

6. Computational error.

Tolerances on the rod OD and clad thickness account for some uncertainties due to heater rod geometry. Also the actual diameter of the heater coil may be different from its nominal size.

Physical property variations occur mainly in the thermal conductivity and specific heat of the insulation and cladding. The investigation of these properties was done on the basis of thermal diffusivities since this parameter is considered to be the most important in transient conduction calculations. It was found that maximum error due to property variation occurred when the thermal diffusivities of the insulation and cladding were disturbed simultaneously. Therefore, this was the case investigated in the analysis.

Measurement errors occur during testing due to inaccuracy of the thermocouple or power measurement. In addition, radial misplacement of the thermocouples results in incorrect data generation.

One of the simplifying assumptions used in DATAR is that angular and axial conduction is neglected. This assumption was made because of the complications involved in a two-dimensional transient calculation. Errors are obtained due to the presence of an insulated thermocouple in the cladding which disturbs the temperature field. If a thermocouple is misplaced radially from its nominal position the results of the data reduction are different from those obtained with a nominally placed thermocouple. Thus, there is further error generated in the results for a misplaced thermocouple relative to a nominally positioned thermocouple.

A quantitative value of uncertainty can be attached to eight of these factors. These uncertainty factors are given below.

1.	Outside Diameter of Rod	- 3 mils
2.	Clad Thickness	+ 10%
3.	Heat Coil Diameter	+ 100 mils
4.	Power Measurement Error	+ 3.16%
5.	Temperature Measurement Error	+ 1.75%

6. Insulation Thermal Diffusivity - 11.5%

7. Clad Thermal Diffusivity - 7.8%

8. Thermocouple Misplacement 10 mils

The remaining three effects must be determined by analysis. These are:

1. Axial Conduction

2. Effect of Thermocouple Presence

3. Numerical Procedure

The error in the calculated local heat transfer coefficient due to each parameter has been investigated analytically by the method discussed below.

A "standard case" was generated assuming boundary conditions similar to those expected under typical FLECHT conditions. These values were further confirmed by the results from the five foot heater rod bench tests. The boundary conditions for the standard case are as follows:

1. T_{fluid} = 292°F (Saturation at 60 psia)

2. $0 < t \leq 5$ sec, h = 2 Btu/hr ft^2 °F

   $5 < t \leq 15$ sec, h = 30 Btu/hr ft^2 °F

   $15 < t \leq 30$ sec, h increases linearly from 30 to 100 Btu/hr ft^2 °F (slow ramp)

   $30 < h \leq 40$ sec, h = 100

3. Power = 1.4 kw/ft

From the above boundary conditions, the temperature behavior at the heater rod thermocouple location was generated by a transient conduction calculation. This solution to the ordinary transient conduction equation was performed by computer.

A data generation code calculated transient temperature profiles which were processed by the data reduction code (DATAR) to reproduce the boundary conditions. A reference condition was established by first using nominal rod dimensions and properties for the data generation and reduction. The effect of each variable was determined by calculating the temperature behavior created by a perturbation in the particular variable of interest. The temperatures generated by the perturbed cases were reduced by DATAR to obtain heat transfer coefficients. Deviations in heat transfer coefficients between the perturbed cases and the nominal case were considered to be the error incurred due to uncertainty in the parameter being investigated.

The effects of axial conduction were assessed by reducing the data generated by an axial-radial two-dimensional code and comparing it with the heat transfer coefficient obtained from a one-dimensional analysis. Similarly, the reduction of data generated by an angular-radial two-dimensional code was used in evaluating the error due to the presence of the thermocouple and misplacement of the thermocouple.

The effects of computational errors were assessed by comparing the heat transfer coefficient obtained from the data reduction of the nominal reference case and the actual boundary conditions of the standard case.

Table 4 presents the calculated maximum error in the heat transfer coefficient due to each source investigated. These errors occurred during the ramp increase in the heat transfer coefficient. This type of film coefficient behavior is of greatest interest, since it is the type of behavior which is expected to occur from the inception of reflooding up to the time of quenching. Examples of the analysis are shown in Figures 13 and 14.

With the exception of the computational error, it was assumed that all the errors are normally distributed. Statistical combination of these errors results in a total distributed error of 4.83 percent. Adding on the non-distributed error gives a total maximum error in the heat transfer coefficient of 12.43 percent.

In order to investigate a worst case, a boundary condition consisting of steps in the heat transfer coefficient from 2 to 30 to 2500 Btu/hr ft^2 °F was examined. The computational error was found to be 16.2 percent. A "fast ramp" boundary condition was also investigated in which the heat transfer coefficient was linearly increased from 30 to 2500 Btu/hr ft^2 °F over one half

TABLE 4

MAXIMUM ERROR IN THE CALCULATION OF HEAT TRANSFER COEFFICIENTS

Source	Error
A. Distributed Error	
1. Outside Diameter of Rod	1.2%
2. Clad Thickness	0.6%
3. Heater Coil Diameter	0.1%
4. Power Measurement	1.1%
5. Temperature Measurement	0.7%
6. Thermal Diffusivity, Clad and Insulation	4.2%
7. Thermocouple Misplacement	1.5%
Total Distributed Error [a]	4.83
B. Non-Distributed Error	
8. Thermocouple Presence	3.6%
9. Axial Conduction	0.8%
10. Numerical Procedure	3.2%
Total Error	12.43%

a. Square root of the sum of the squares of the distributed errors.

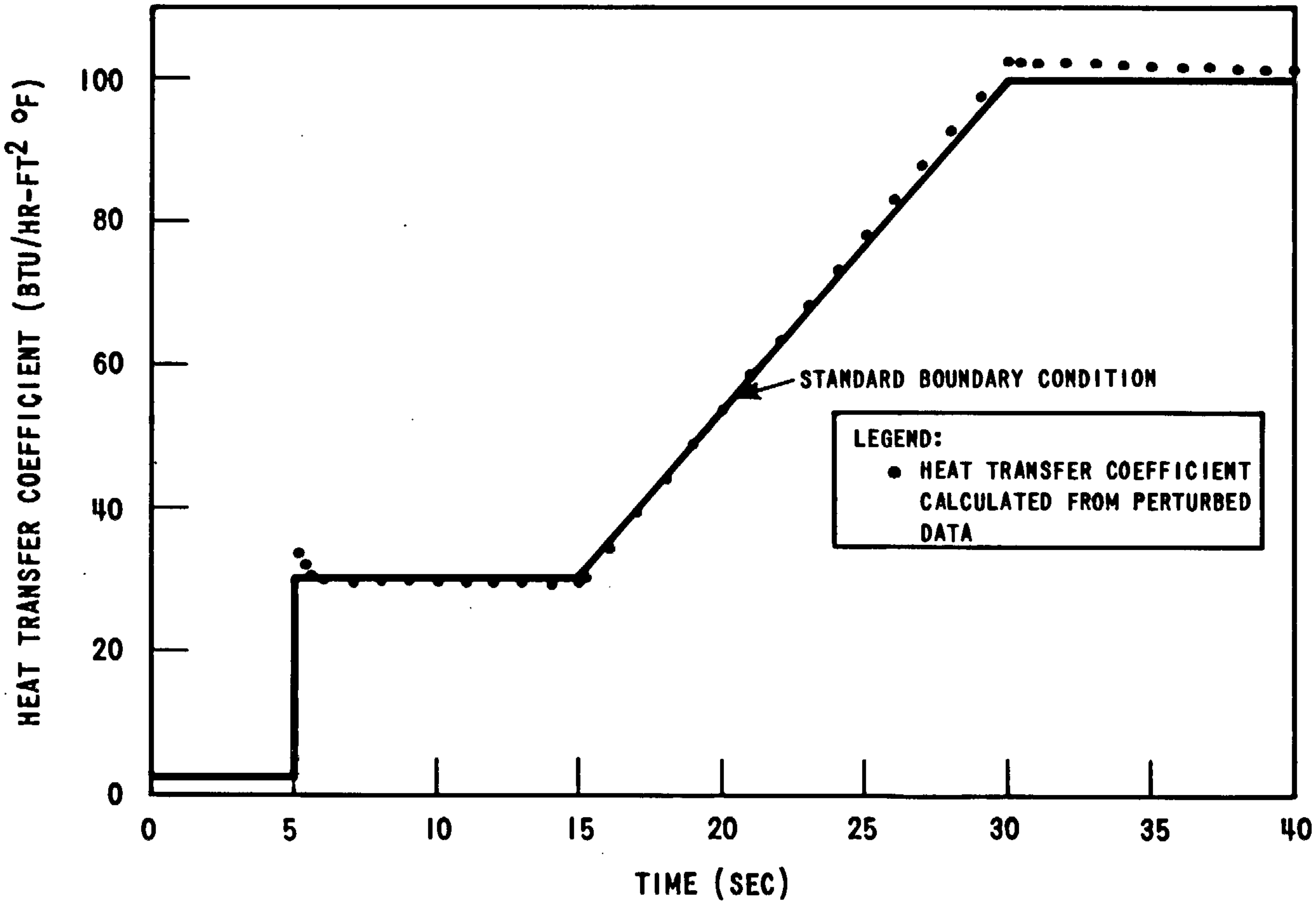

Figure 13. FLECHT Error Analysis, Slow Ramp Case, Temperature Measurement Error + 1¾ Percent

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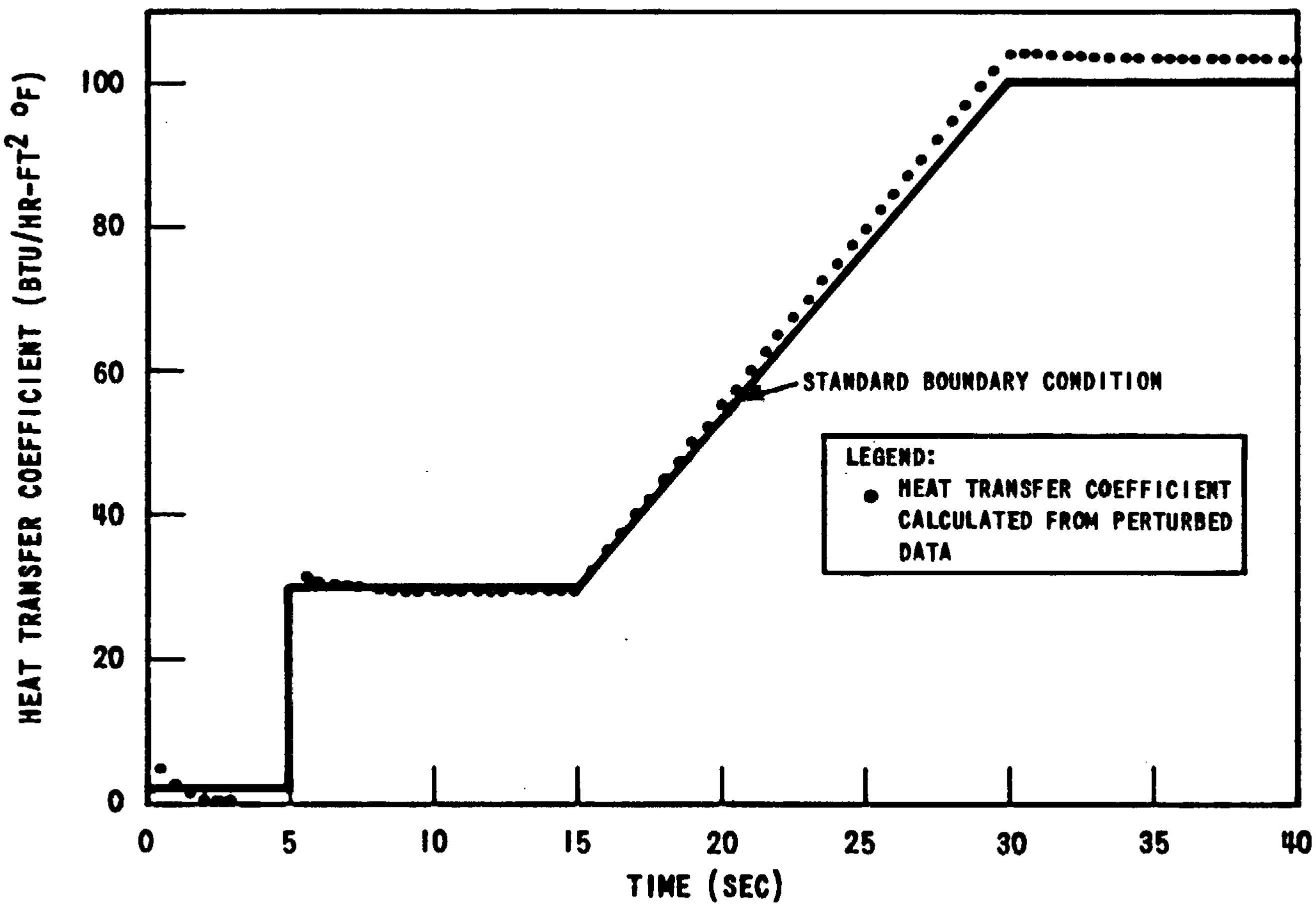

Figure 14. FLECHT Error Analysis, Slow Ramp Case, Rod O.D. Error - 3 Mils

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second. The computational error for the fast ramp was found to be 8.6 percent. Thus, it is obvious that more severe changes in heat transfer coefficient lead to increased error in data reduction.

Nonetheless, it is felt that an error analysis based on the slow ramp boundary conditions are representative of the errors to be expected in the FLECHT tests. A rapid rise in the heat transfer coefficient occurs during the quenching of the heater rods; however, the main concern with regard to the heat transfer coefficient is in the region prior to quenching. Thus, the error analysis is based on pre-quench conditions.