REPORT NO. ACNP-6011

OPERATING CONTROL RODS FOR THE ENRICO FERMI ATOMIC POWER PLANT

FINAL DESIGN REPORT

PERFORMED BY ALLIS-CHALMERS MFG. CO. NUCLEAR POWER DEPT. - GREENDALE FOR ATOMIC POWER DEVELOPMENT ASSOCIATES , INC. 1911 FIRST STREET DETROIT 26, MICHIGAN

OPERATING CONTROL RODS

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BY

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November 8, 1960

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ABSTRACT

The final design of the operating control rods for the Enrico Fermi Atomic Power Plant was completed. Two such rods are located near the center of the reactor, which is sodium cooled. Boron carbide is used as poison material. A flow distribution test and analysis, thermal analysis, and stress analysis of the rod was performed for both the normal operating and scram conditions. The test and analysis shows that the design meets APDA specifications.

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I. INTRODUCTION

The final design of the operating control rods for the Enrico Fermi Atomic Power Plant is shown in Figure I. Two such rods are located within guide tubes near the center of the reactor core. Design characteristics of the rods are given in Table I.

Each operating rod contains approximately 342 grams of boron carbide poison enriched to 25.5 per cent by weight in the isotope B-10. The poison material is disposed equally in nineteen stainless steel tubes set on a triangular pitch, spaced and supported at the bottom by the poison rod support grid, and near the middle and top by tube sheets.

The stainless steel poison tubes are designed to contain the six liters of helium gas generated during ten months of service and to facilitate the removal of the heat generated through absorption of neutrons in the poison material, slowing down of the neutrons by the rod, and gamma heating in the rod components and coolant.

TABLE I. DESIGN CHARACTERISTICS OF OPERATING RODS

Operating Rod Dimensions	
Length	42-17/64 in.
Diameter of rod at colmony rings	2.362 + .000 -.005 in.
Nominal outside diameter for poison section	2.250 in.
Weight in air	16 lbs.
Weight in sodium	13 lbs.
Poison Tubes	
Number of tubes	19
Nominal outside diameter	5/16 in.
Wall thickness	0.028 in.
Nominal helium gap at operating temperature	0.0015 in.

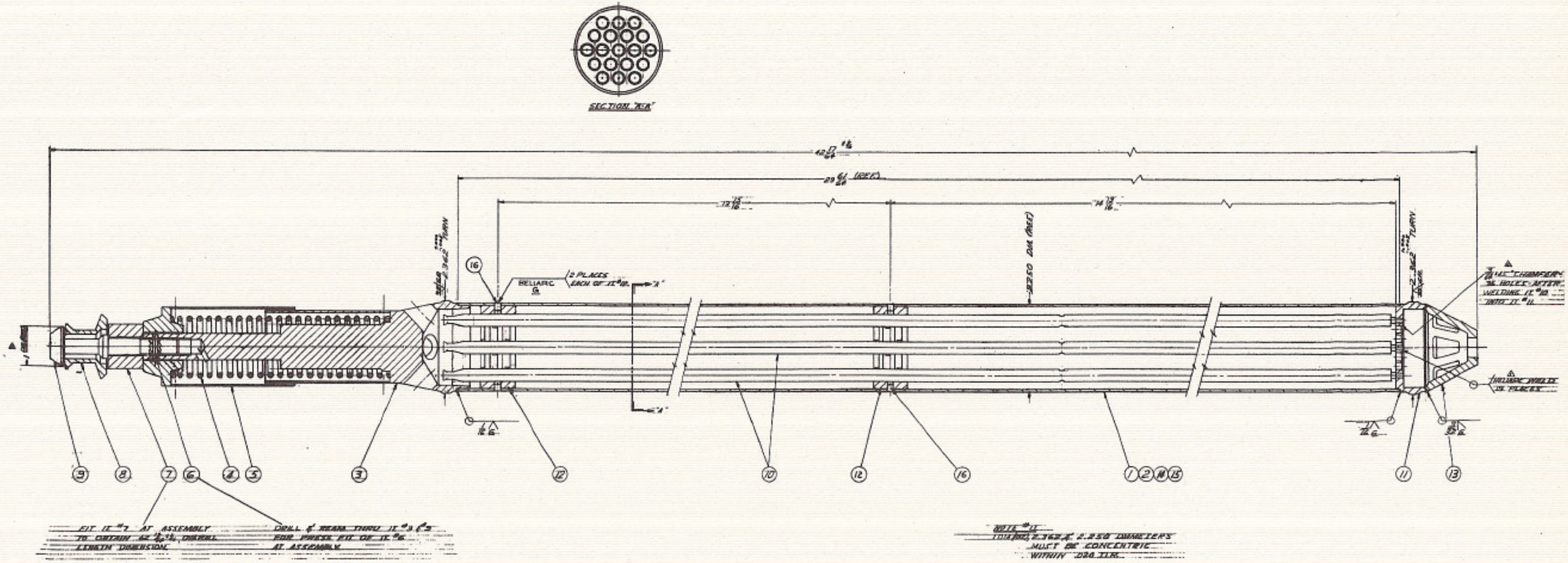


Figure 1. Operating control rod. Code: 2) outer shell; 3) delatching spring lower housing assembly; 4) delatching spring; 5) delatching spring upper housing assembly; 9) pin head; 10) poison rod assembly; 11) poison rod support grid; 12) tube sheet assembly; 13) inlet nozzle. (A-C Dwg. 43-500-813).

The heat generated in the rod is removed by the liquid-sodium coolant, which is supplied through pressure breakdown orifices from the coolant inlet plenum. The coolant passes through a seat-stem assembly in the lower guide tube, flows both through and around the operating rod, and then flows through the upper portion of the guide tube to the upper pool.

A coolant-flow analysis, thermal analysis, and stress analysis of the rod for both normal operating and scram conditions were made to insure that the final design met APDA specifications.

2. HEAT GENERATION RATES WITHIN THE OPERATING ROD FOR THE NORMAL OPERATING AND SCRAM CONDITIONS

The heating rates[1] used in designing the operating rod are as follows:

The total heating in the operating rod during normal operation at a reactor power of 430 mw is 368 watts/cc. This heating rate consists of the following components:

$$\text{Neutron capture} = \frac{80{,}000}{B_4C \text{ volume in cc/rod}} \text{ watts/cc}$$

Gamma heating = 25 watts/cc
Neutron slowing down = 45 watts/cc

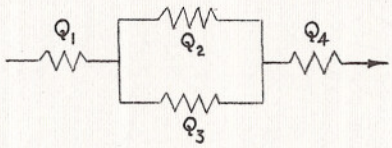
The boron carbide poison volume is 268.2 cc/rod.

The total heating rate in the operating rod one minute after scram from 430 mw reactor power is 34.6 watts/cc. This heating consists of the following components:

Stainless steel = 23 watts/cc
Sodium = 2.3 watts/cc
Boron carbide = 9.3 watts/cc

3. COOLANT-FLOW ANALYSIS

The flow distribution through the guide tube and rod is as follows:



where,

Q_1 = flow through the seat-stem
Q_2 = flow through the rod
Q_3 = by-pass flow through the annulus formed by the guide tube and outer shell of the control rod assembly
Q_4 = flow through the upper portion of the guide tube

The pressure drop through the seat-stem, H_1, is composed of the following losses:

1) entrance and friction loss through the stem pipe
2) expansion loss where the flow enters the seat section
3) friction loss through the seat section
4) entrance and exit losses through the seat orifices

The pressure drop through the operating rod, H_2, is composed of the following losses:

1) entrance loss through the inlet nozzle
2) entrance and exit losses through the poison rod support grid
3) friction loss through the rod bundle
4) entrance and exit losses through the tube sheets
5) exit loss from the rod

The pressure drop through the annulus formed by the outer shell of the rod and the guide tube, H_3, is composed of the entrance, friction, and exit losses.

The pressure drop through the upper portion of the guide tube, H_4, is composed of the following losses:

1) friction loss through the annulus formed by the spring enclosure tube and guide tube
2) entrance and friction loss through the annulus formed by the cocking tube and guide tube
3) entrance and friction loss through the annulus formed by the actuator shaft and guide tube
4) exit loss on leaving the guide tube to the upper pool

The flows through the four major flow passages, Q_1, Q_2, Q_3, and Q_4, were calculated by first establishing an equation relating the head loss and flow for each of the flow passages. The equations for Q_1 and Q_4 were established by calculations. The equations for Q_2 and Q_3, because of the complexity of the flow passages, were established using the results of a flow test. This test is discussed in detail in Section 4. In all calculations, friction factors, roughness factors, and entrance and exit coefficients given in standards of the Hydraulic Institute [2] were used.

The equations which were thus established are as follows:

$$H_1 = 0.016\, Q_1^{1.969} \tag{1}$$

$$H_2 = 0.0174\, Q_2^{1.589} \tag{2}$$

$$H_3 = 0.230\, Q_3^{1.745} \tag{3}$$

$$H_4 = 0.00245\, Q_4^{1.947} \tag{4}$$

where the head losses are expressed in feet of sodium and the flows are expressed in gallons per minute. Since the stroke of the rod is small, the equations were taken to be valid for both cases; i.e. when the rod is in the normal operating position and in the scram position. The head loss across the pressure breakdown orifices are given in Allis-Chalmers Report ACNP-5705[3] for various flows. The pressure losses, H_2 and H_3, are equal.

With the reactor operating at 430 mw and with the rod in the normal operating position, the available driving head from the lower inlet plenum is 90 psi. With the equations given, the following results were obtained. The total flow through the system is 52.5 gpm. Of this total flow, 38.1 gpm flows through the rod and 14.4 gpm flows around the rod.

One minute after reactor scram from normal operating condition, the total available driving head from the lower inlet plenum is 0.25 psi. Results of calculations were as follows. The total flow through the system is 2.7 gpm. Of this total flow, 2.22 gpm flows through the operating rod and 0.48 gpm flows between the rod shell and guide tube.

4. FLOW TEST

According to specifications, the calculated coolant pressure drop must be such that during reactor shutdown with 40 per cent of full coolant flow or 16 per cent of normal core pressure drop, the lifting force on the rod using calculated pressure drops must be less than one half of the weight of the rod in sodium. The weight of the rod in sodium is 13 lbs.

A flow test was conducted to determine flow rates and pressure drops through the operating rod and the lifting force was then calculated. This test was necessary because the complexity of the flow passage made it very difficult to calculate these values accurately.

The test loop is shown in Figure 2. Water at a temperature of 180 F is used as fluid. Water at this temperature has approximately the same viscosity as sodium at 700 F. The water temperature was held constant by bubbling steam through the water in the tank. The flow rate through the test section was varied by adjusting valves (1) and (2). Pressure drop across the test section was measured with a

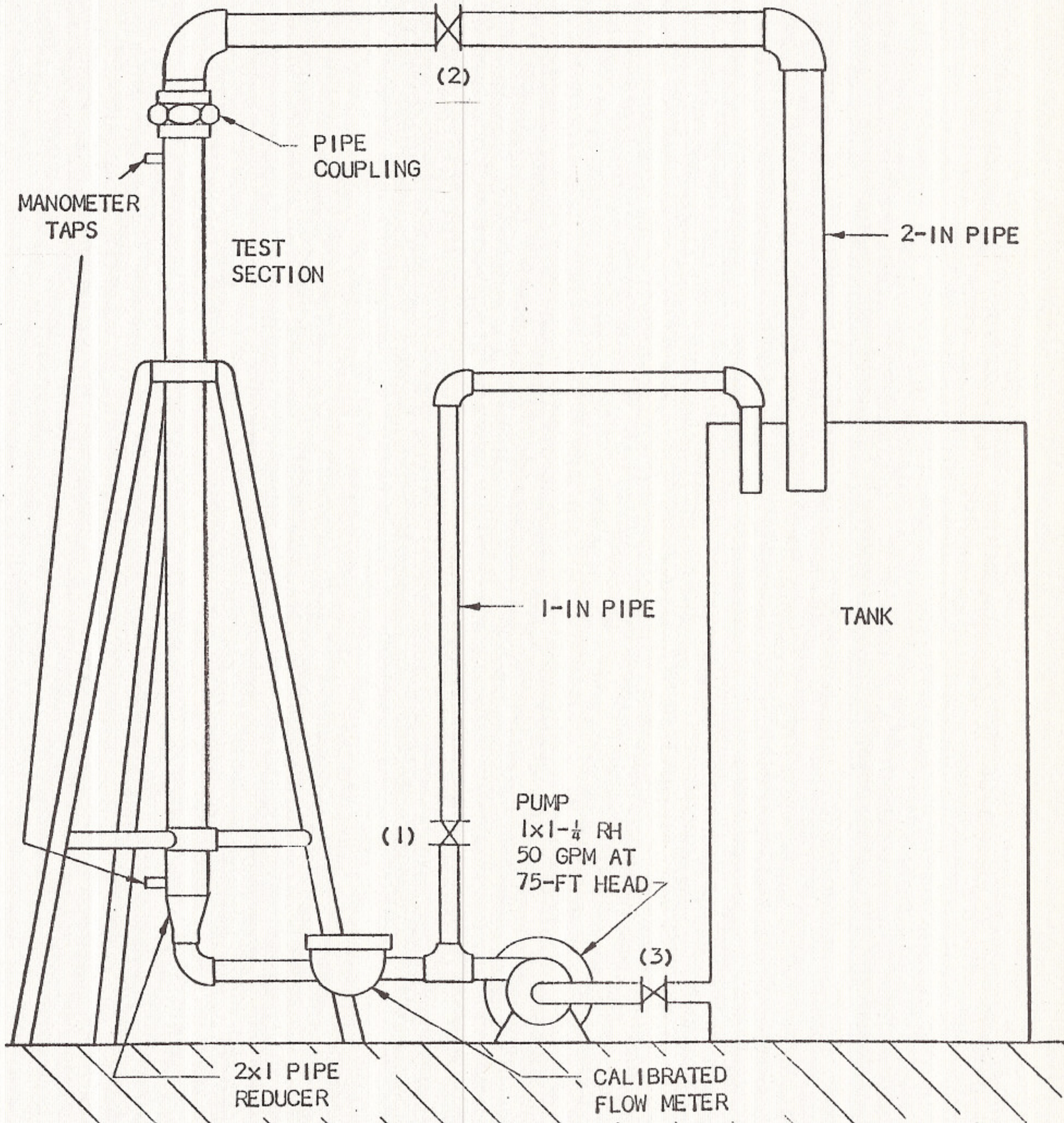


Figure 2. APDA operating rod - flow test schematic (A-C Dwg. 43-024-253)

mercury manometer. To convert results obtained with water to those for sodium, a density correction factor was applied.

A dummy rod (Figure 3 and 4) having flow passages identical to those of the operating rod was used for the test. In the initial test, a poison rod support grid similar to that shown in Figure 5 but without the twelve 5/32-in dia. holes was used. The pressure-drop-flow curve for this test is given in Figure 6. At 21 gpm (40 per cent of normal operating full flow) the drop across the rod was 2.05 psi, which would result in a lifting force of 9 lb. on the operating rod, which is excessive.

Twelve 5/32-in dia. flow holes as shown in Figure 5 were drilled in the poison rod support grid and the test was re-run. The results of this test are presented in Figure 7. At 21 gpm, the drop across the rod is 1.58 psi, which results in a lifting force on the rod of 6.93 lbs. This provides a safety factor of 1.88, which is sufficiently close to the value of 2.0, which was specified for a calculated value of the pressure drop across the rod.

To determine the by-pass flow (Q_3) the inlet nozzle of the operating rod was blocked thus forcing the flow into the annular passage around the rod. Results of this test are presented in Figure 8. The by-pass flow is approximately 26 per cent of the total flow.

5. THERMAL ANALYSIS OF THE OPERATING ROD

5.1 Coolant Temperature

The coolant temperature through the operating rod channel was calculated using the general equation:

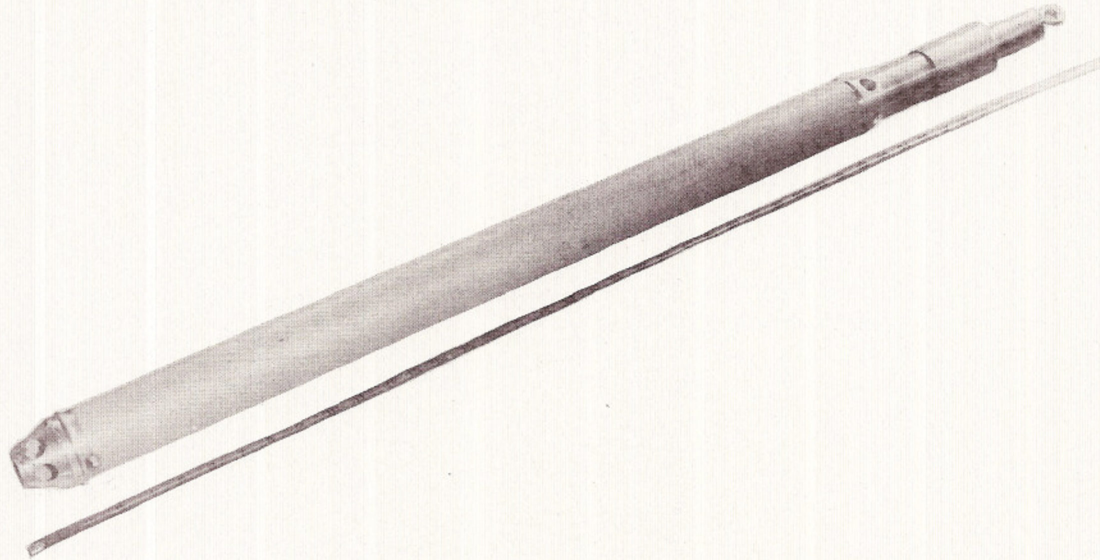


Figure 3. APDA operating rod flow test section.

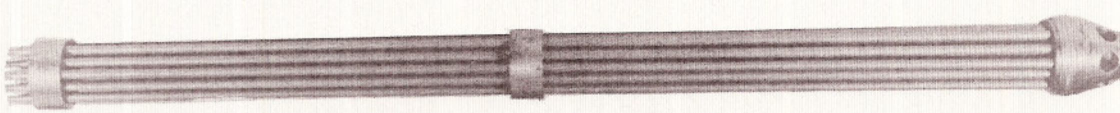


Figure 4. APDA operating rod flow test section.

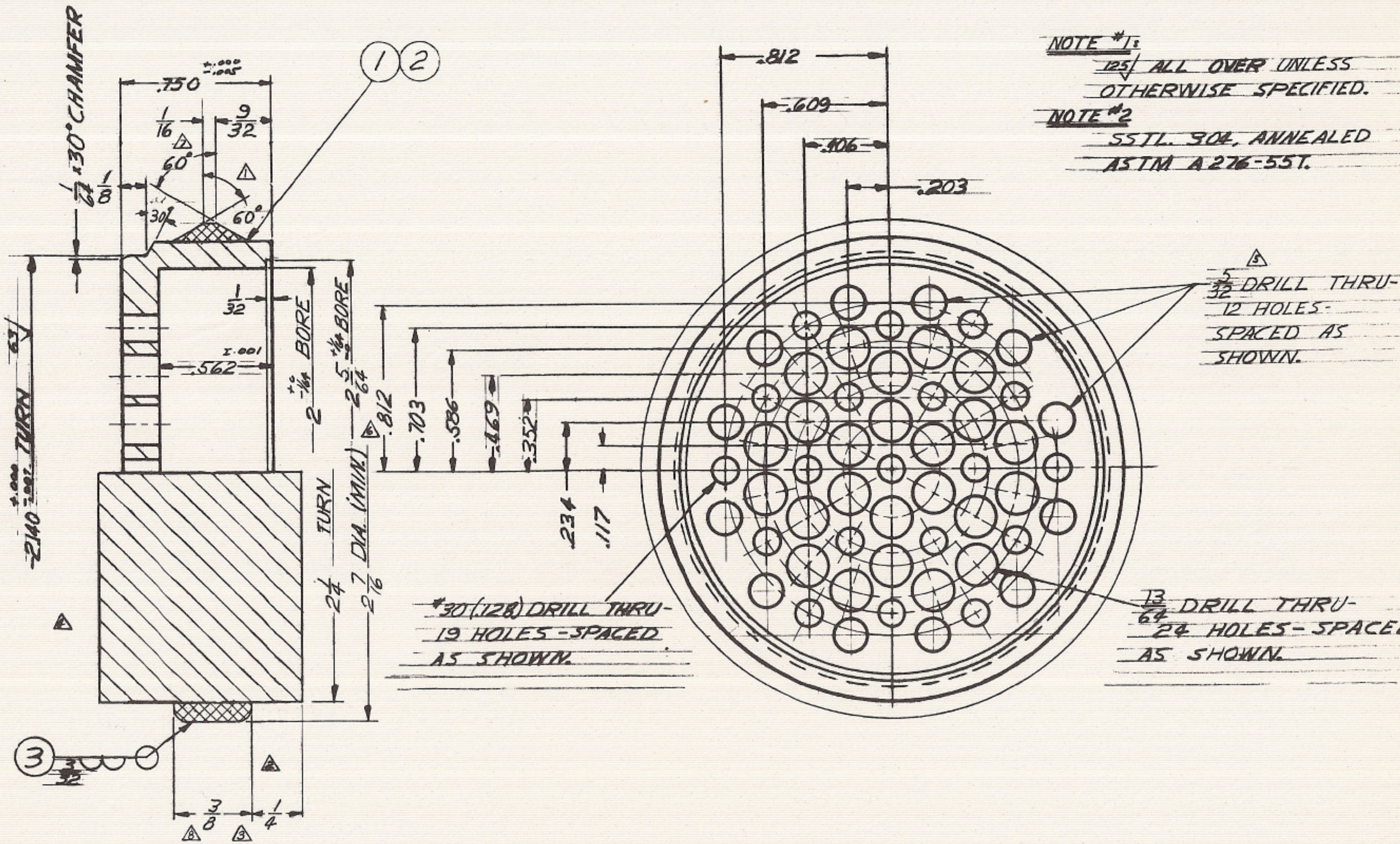


Figure 5. Poison rod support grid. (A-C Dwg. 43-201-979)

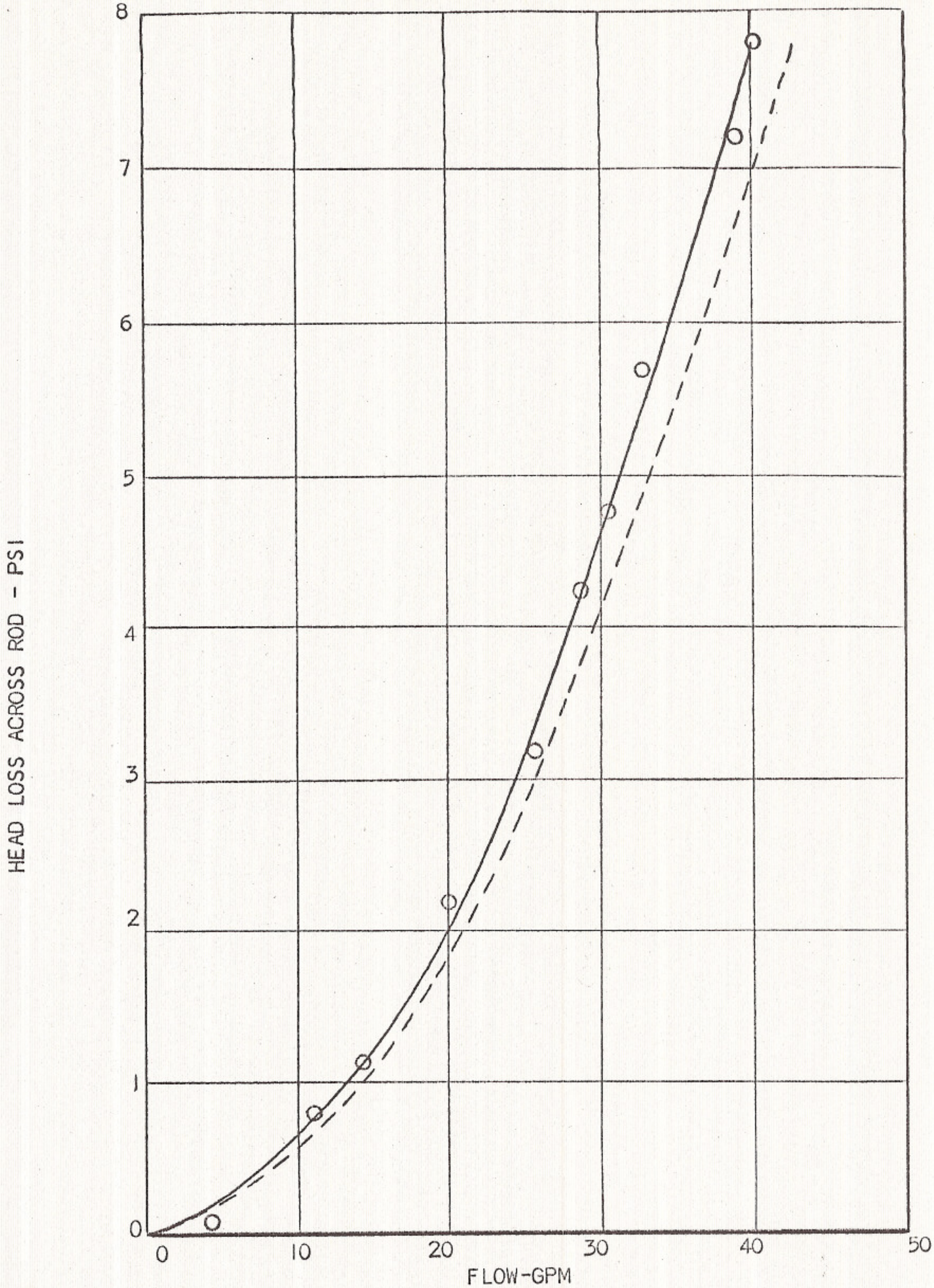


Figure 6. Test data for initial flow test. Solid curve shows test results with poison rod support grid without the twelve 5/32-in. dia. holes. Dotted line represents results correlated to sodium at 700 F. (A-C Dwg. 43-024-237)

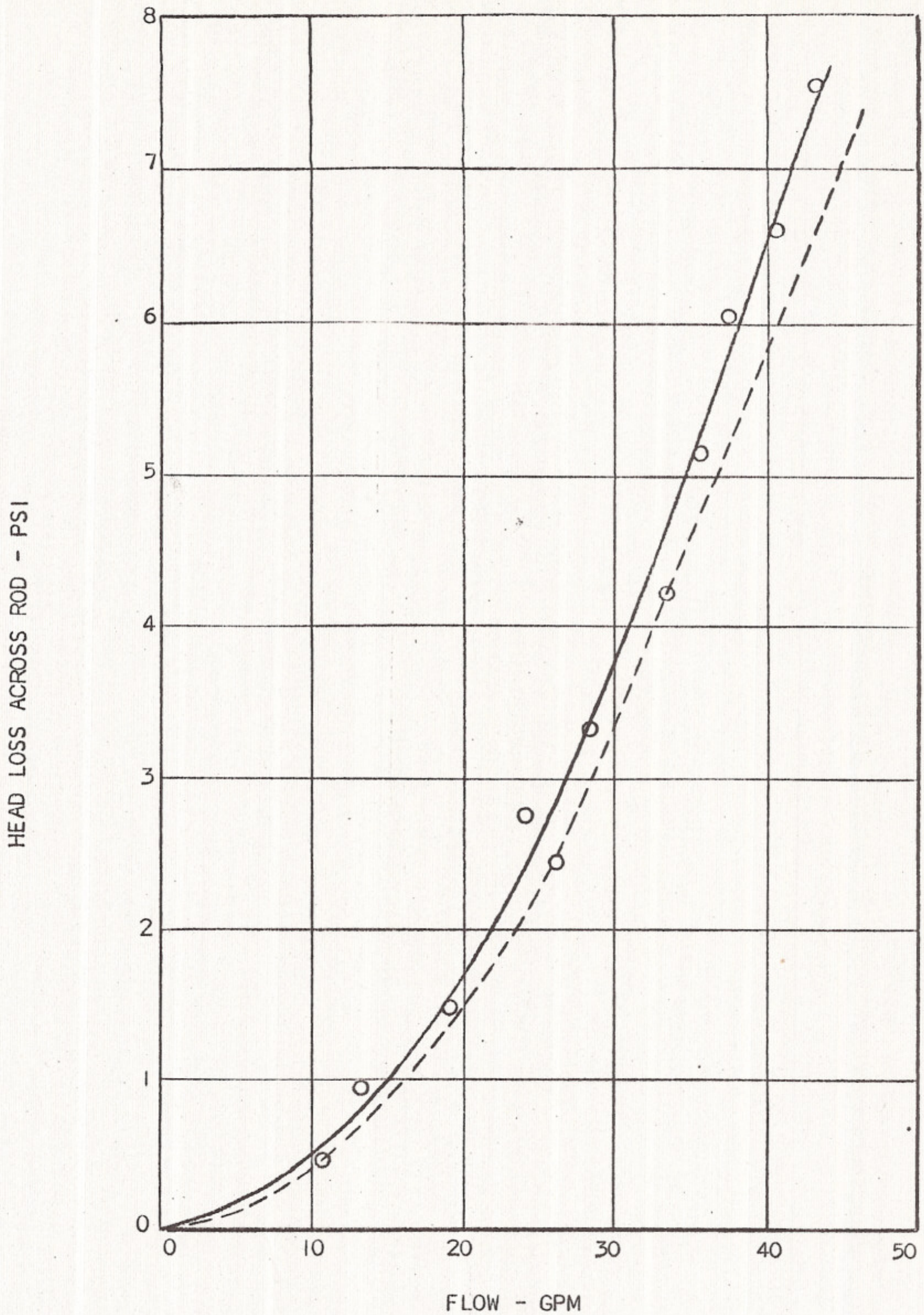


Figure 7. Test data for flow test of final design. Solid curve shows test results with twelve 5/32-in. dia. holes in poison rod support grid. Dotted curve represents test results correlated to sodium at 700 F. (A-C Dwg. 43-024-239)

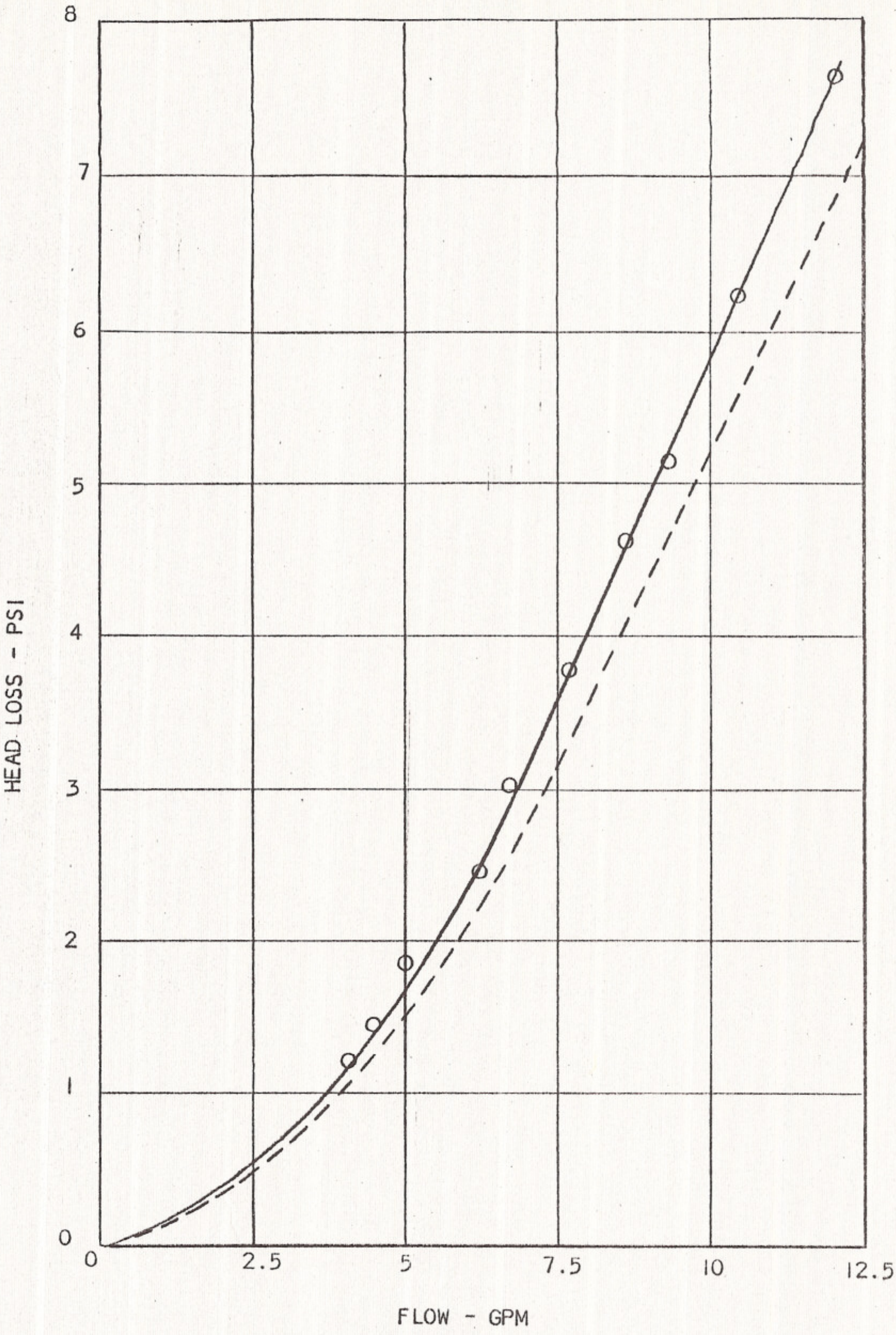


Figure 8. Test data for flow by-passing operating rod. Solid line shows test results. Dotted line represents results correlated to sodium at 700 F. (A-C Dwg. 43-024-238)

$$Q\,C_p \frac{dT}{dx} = K_1 (T_o - T) + K_2 \sin \frac{\pi x}{L} \quad (5)$$

where,

Q = coolant flow rate, lb/hr
C_p = heat capacity, BTU/lb
T = coolant temperature, °F
T_o = temperature of coolant in surrounding fuel elements
K_1 = calculated heat transfer coefficient between coolant in surrounding elements and coolant in operating rod
K_2 = internal heat generation rate in operating rod
L = extrapolated core length to approximate gamma and neutron heating with a sine curve

In the region where the flow divides and flows between the rod and guide tube and through the rod, the temperature was calculated with the following equations:

$$Q_1 C_p \frac{dT_1}{dx} = K_1 (T_o - T_1) + K_2 (T_2 - T_1) \quad (6)$$

$$Q_2 C_p \frac{dT_2}{dx} = K_3 (T_2 - T_1) + K_4 \sin \frac{\pi x}{L} \quad (7)$$

where,

Q_1 and T_1 = the flow rate and temperature of the coolant that flows around the operating rod
Q_2 and T_2 = the flow rate and temperature of the coolant flowing through the operating rod
$K_1, K_2 \ldots$ = calculated heat generation and heat transfer coefficients.

The flow rates for the equations are based on results of the flow and pressure drop test. The simultaneous equations were solved by the method of undetermined coefficients.

In evaluating the heat transfer coefficients, the film conductions were evaluated from the Martinelli equation,[4]

$$\frac{hD}{K} = 7 + 0.025 \left(\frac{DuPc}{K}\right)^{0.8} \quad (8)$$

The temperatures were calculated assuming that the material and coolant had an average temperature of 700 F. Axial heat transfer was assumed to be negligible. Internal heat generation was approximated by a sine curve based on the extrapolated length of the core calculated from APDA curve No. 20-3-A, Rev. No. 3. Internal heating in the region immediately surrounding the rod assembly contributed very little to the heating of the coolant compared to the heat introduced by the surrounding fuel elements. The temperature of the coolant in the surrounding elements was assumed to be as shown in APDA curve No. 20-3-D-1, and was based on the hottest channel at 430 mw operation.

Results of calculations for the case when the poison is centered three inches above the core centerline and the reactor is operating at 430 mw are shown in Figure 9. The coolant temperature one minute after scram with the poison in the same position is shown in Figure 10.

5.2 Cladding and Poison Temperature

The temperature of the cladding and poison were determined by the relaxation method. The poison temperatures calculated are given in Figure 11.

In determining the temperatures expected in the hottest poison rod (Figure 11, Curve A), hot spot factors based upon the following assumptions were used:

1) The coolant temperature was 50 F above the calculated maximum temperature.
2) The poison was perfectly centered in the cladding and had a uniform helium gap insulating it from the cladding.
3) The helium gap between the cladding and poison was the largest possible with the specified manufacturing tolerances.

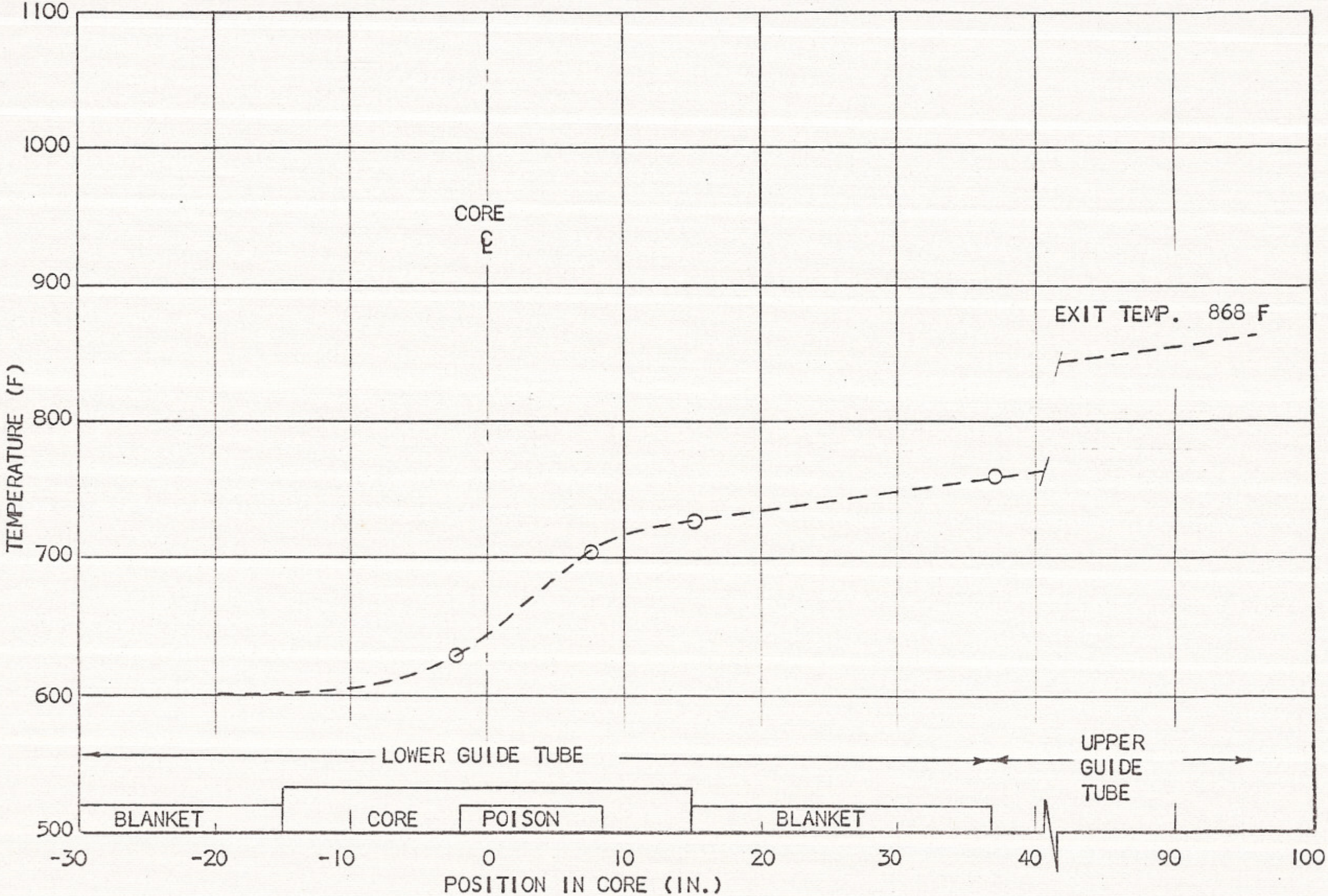


Figure 9. Coolant temperature in rod during normal operation at 430 mw. Coolant flow is 52 gpm. (A-C Dwg. 43-024-258)

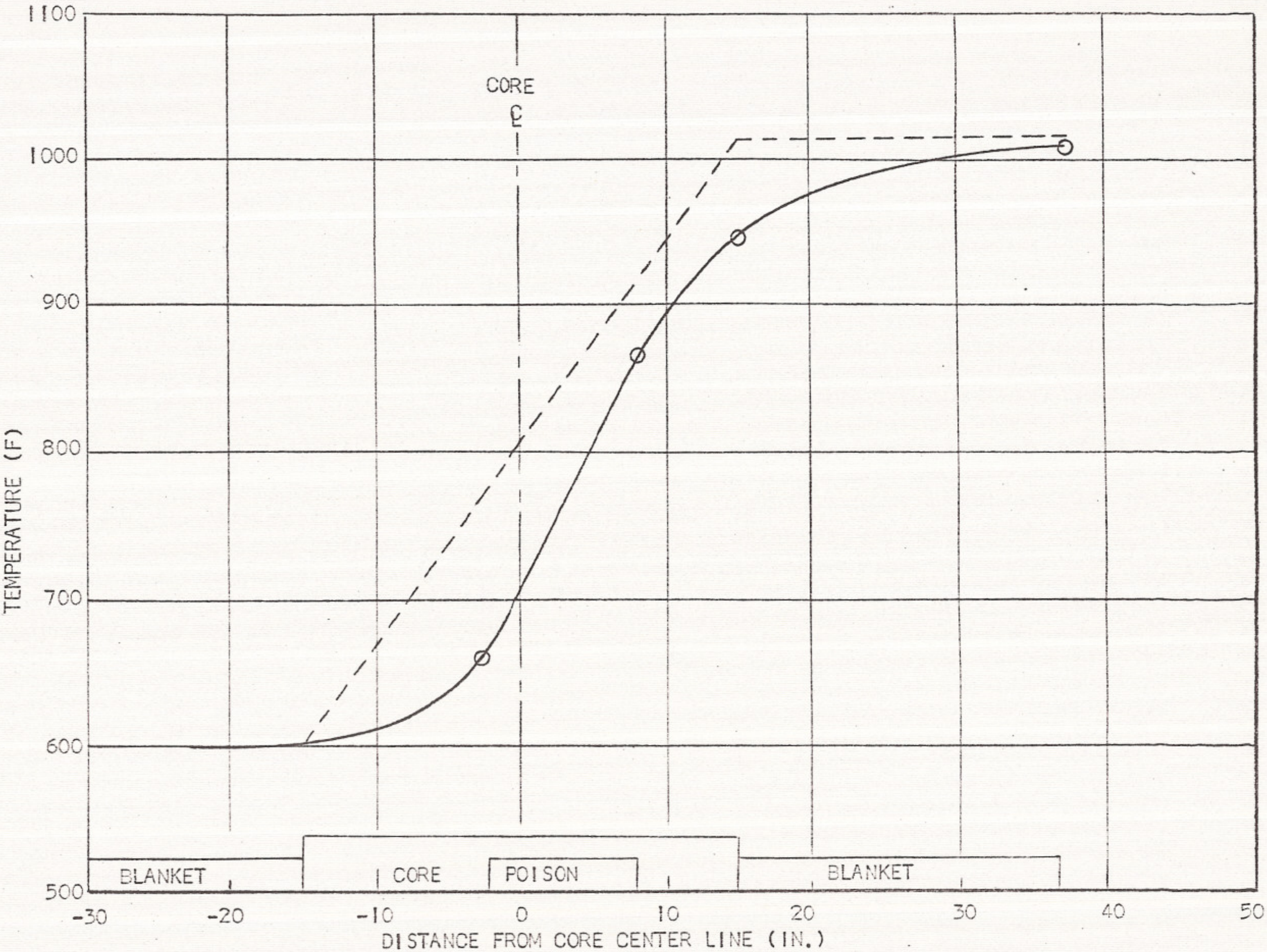


Figure 10. Coolant temperature in rod one minute after scram from full power. Flow through rod is 2.7 gpm. Solid curve shows coolant temperature. Dotted curve shows temperature in surrounding fuel elements. (A-C Dwg. 43-024-259)

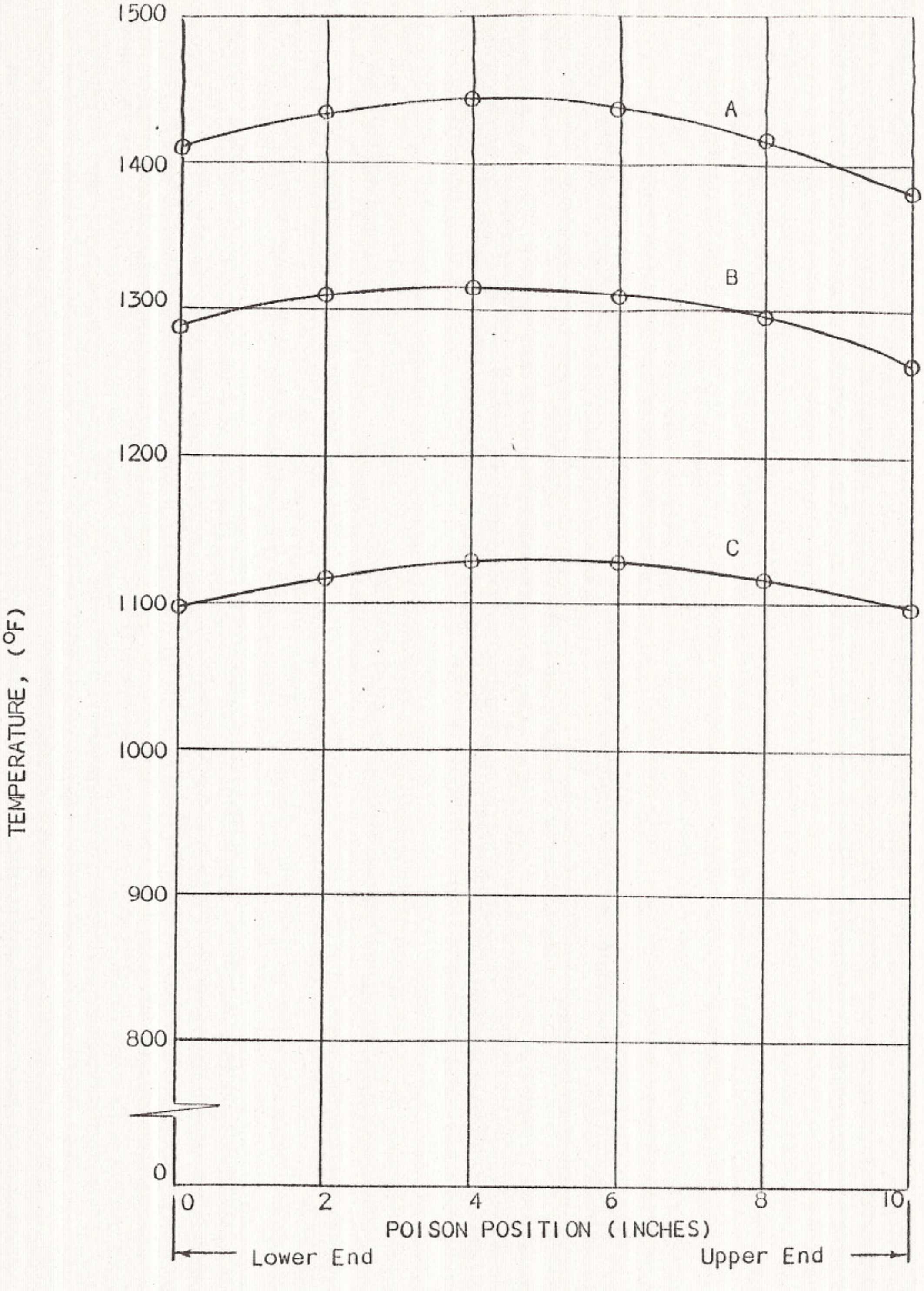


Figure 11. Temperature of poison. Curve A is temperature at centerline of hottest poison with hot spot factors. Curve B is temperature at centerline of average poison with poison centered in tube, Curve C is average poison temperature over total cross section. (A-C Dwg. 43-024-260)

The average poison temperatures (Curves B and C) were based on average coolant temperature and manufacturing tolerances but again assumed that the poison was centered within the cladding.

The cladding temperatures given in Table 2 were also calculated by the relaxation method. The maximum cladding temperature was calculated assuming the following:

1) The coolant was 50 F above the average temperature
2) The poison was not centered in the poison tube and all the heat from the poison was transferred through one half of the poison tube.

The resulting maximum cladding temperatures along with the corresponding average temperatures are listed in Table 2.

TABLE 2. POISON-TUBE CLADDING TEMPERATURES

Condition	Maximum	Average
	(F)	(F)
at 430 mw operation	920	789
one minute after scram from 430 mw	927	872

6. THERMAL STRESSES IN GUIDE TUBE AND ROD COMPONENTS

6.1 Steady-State Conditions

The following is a tabulation of the calculated maximum thermal stresses in the poison cladding and in the guide tubes during 430 mw operation and one minute after scram from 430 mw operation.

TABLE 3. STEADY-STATE THERMAL STRESSES

Component	Thermal Stress (psi)	
	430 mw operation	One minute after scram
Poison cladding	16,900	1,020
Lower square guide tube	10,500	4,200
Lower round guide tube	9,600	4,590
Upper guide tube	22,210	707

Thermal stresses were determined by calculating the temperature gradient across the members by relaxation methods and calculating the stress with the methods outlined by Timoshenko.[5]

6.2 Transient Condition

According to information available from APDA, a thermal transient of 20 °F/sec to a maximum difference of 300 F is possible in the control rod coolant. High transient thermal stresses in the rod components are, therefore, possible.

Transient thermal stresses were calculated assuming an instantaneous temperature change of 300 F. A cycle life was predicted on the basis of the calculated stresses and thermal fatigue data reported by Coffin.[6] All components of the rod were found to be able to withstand with safety considerably more temperature cycles than could be expected during the lifetime of the rods.

7. MECHANICAL STRESSES IN THE OPERATING ROD

7.1 Poison Cladding

The poison is placed inside the nineteen tubes with an outside diameter of 5/16 in. and a nominal wall thickness of 0.028 in. When the expected 6 liters of helium are heated to 1200 F, the design temperature, this results in an internal pressure of 1047 psi and a maximum hoop stress of 4650 psi, which is less than that allowed by Section VIII of the ASME Boiler Code.[7] The discontinuity stresses at the ends of the tubes were calculated to be 4750 psi by methods outlined by Timoshenko[8] and assuming full restraint of the tube at the end.

Burst tests (Section 8) of the tubes showed that they failed well away from the ends and by circumferential stress, indicating that the assumptions made in the analytical analysis were conservative.

The poison tubes are free to move axially in the tube sheets. Calculations using Euler's formula show that a restraining force of 282 lbs. is necessary to buckle the 5/16-in o.d. tubing and that major buckling will occur before local buckling. The design of the tube sheet (Figure 12) is such that loads approaching this value are not probable. The tube sheet is designed and accurately constructed to give positive but elastic support to each individual tube.

7.2 Outer Shell

The outer shell must withstand the 1500-lb compressive load that the handling mechanism can apply. This tube acts as a short column and can withstand a compressive load of 2700 lb using the permissible stress for 304 stainless steel at 1200 F given in Section VIII, ASME Boiler Code.

8. POISON CONTAINMENT TUBE DESIGN ANALYSIS

To evaluate the end closure welds and the center plug design three poison tube test sections were subjected to a burst test. As in the case of the poison tubes for the safety rods, [9] the tubes failed due to hoop stress in the tube wall (see Figure 13). The rolling of the tube into the center plug appears to have no effect on the strength of the tube wall at that section. In all cases, failure occurred at approximately 16,000 psi internal pressure. There was no indication that the rolled-in center plug had loosened in any of the test sections.

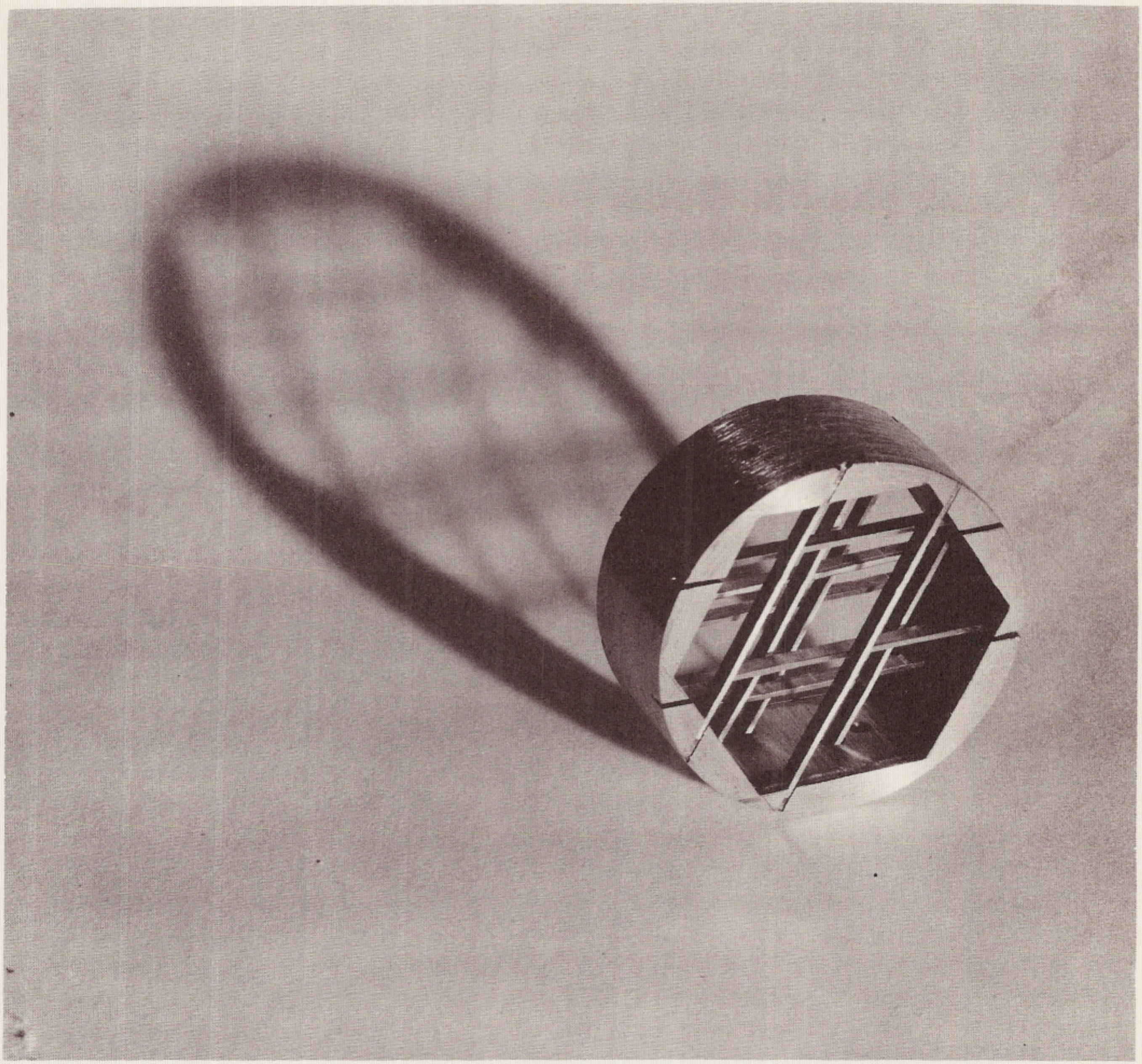


Figure 12. Operating rod tube sheet. (A-C Photo 211256)

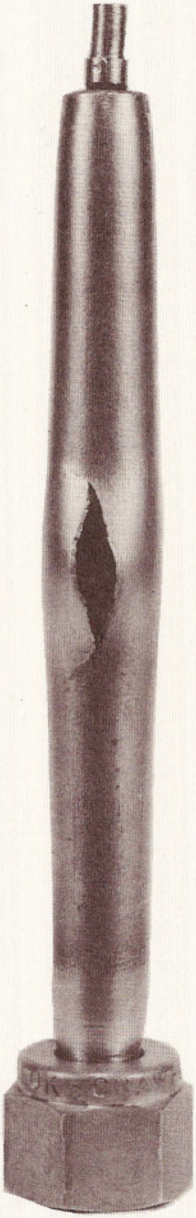


Figure 13. Failure of poison tube in burst test

Calculation of the natural frequency of the poison tubes show that this frequency is above the 100 cps required by the specifications. For the section between the poison rod support grid and the first tube sheet, the natural frequency is 122 cps. This calculation assumed the worst case, i.e. where the poison is attached to the tube and vibrates with it.

For the section of poison tube between the tube sheets, the natural frequency was calculated to be 150 cps. In both cases, the ends of the tube sections were assumed to be simply supported.

9. CONCLUSIONS

Analysis of the final design of the operating control rod for the Enrico Fermi Atomic Power Plant to determine operating characteristics and to show that it has met APDA specifications has been completed. The pressure drop across the rod at 40 per cent full coolant flow is 1.58 psi, which is equivalent to a lifting force on the rod of 6.93 lbs. This provides a safety factor against floating of the rod of 1.88.

Coolant flow characteristics through the operating rod are as follows: The flow rate when the reactor is operating at 430 mw is 52.5 gpm. After scram the flow rate is 2.7 gpm. The flow rate at 40 per cent full flow is 21 gpm. Seventy-four per cent of the coolant flows through the poison section and 26 per cent flows through the annular section formed by the rod and guide tube.

The coolant temperature on entering the operating rod is 600 F. The exit temperature during operation at 430 mw is 868 F. The exit temperature one minute after scram is 1011 F, assuming the temperature in the surrounding elements and pool is at 1012 F.

The maximum temperature of the poison tubes at 430 mw operation is 920 F. The maximum temperature of the poison tubes one minute after scram from 430 mw operation is 927 F. The maximum temperature of the poison is 1445 F. The natural frequency of the poison tubes is greater than 120 cps, which is sufficiently higher than the 100 cps specified.