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UC-80

EXPERIMENT DESCRIPTION
FOR PNL MIXED OXIDES (UO₂-PuO₂)
IRRADIATIONS IN THE GENERAL ELECTRIC
TEST REACTOR

T. B. Burley and J. E. Hanson

June 1970

AEC RESEARCH &
DEVELOPMENT REPORT

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ERRATAAPPENDIX CALCULATION REFERENCES

This page, A-37, replaces the existing page in this document.

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FFTF Fuels Department
FFTF Division

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ABSTRACT

A fuel irradiation test program and capsule design is described for the evaluation of the steady state and transient performance characteristics of prototypic FTR length fuel pins. The fuel pins to be tested comprise 31 in. of mixed oxide ($75\% \text{UO}_2$ - $25\% \text{PuO}_2$) fuel pellets clad in 0.250 in. diameter type 304 stainless steel. The fuel pellets are 93% of theoretical density (TD) and with a 0.006 in. diametrical gap the fuel has an 88% TD smeared density. The capsule is a NaK bonded instrumented assembly designed to produce a fuel pin cladding surface temperature of 800 °F and fuel central temperature of 4000 °F when the fuel pin is producing 14.5 kW/ft (axial peak). The safety analysis, heat transfer calculations and operating instructions are also described.

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INTRODUCTION AND SCOPE

As part of the FFTF-FTR driver fuel development program, a series of irradiations of prototypic FTR-length fuel pins in the GETR is required. The objectives of these tests are to provide irradiation experience with prototypic FTR-length fuel pins under typical FTR conditions of linear heat generation rate and cladding surface temperatures. These irradiations will also provide fuel specimens for subsequent transient irradiation in TREAT to study transient overpower fuel cladding failure mechanisms and thresholds.

The principal test parameters summarized in Table 1 are fuel form, burnup, and the control of axial fuel motion during transient (in TREAT) melting of fuel.

SUMMARY

This document contains design and operating information pertinent to the irradiation of 12 instrumented capsules in pool positions in the GETR. Nominal operating conditions and summaries of principal capsule design and fabrication data are also tabulated in this report.

EXPERIMENT REQUIREMENTS

FUEL PERFORMANCE REQUIREMENTS

The GETR-TREAT capsules typically comprise 31 in. of stainless steel-clad mixed oxide (75% UO_2 - 25% PuO_2) pellets with 1/2 in. long depleted UO_2 pellet at each end of the column. Clad surface temperatures and fuel central temperatures of 800 °F and 4000 °F, respectively, are required. In order to obtain these conditions, the heat generation rate

TABLE 1. Summary of Principal Test Parameters

<u>Capsule Number</u>	<u>Heat Generation Rate, kW/ft</u>	<u>Fuel Form</u>	<u>Smear Density, % TD</u>	<u>*Axial Fuel Motion Restrictors</u>	<u>Average Burnup, MWd/MTM</u>	<u>Subsequent Transient Irradiation</u>	<u>Number of Cycles in Reactor</u>
1	14.5	Solid	88	Yes	10,000	Yes	3
2	↓	↓	↓	No	↓	Yes	3
3	↓	↓	↓	Yes	↓	No	3
4	↓	↓	↓	No	↓	Yes	3
5	↓	↓	↓	Yes	↓	Yes	3
6	↓	↓	↓	No	↓	No	3
7	↓	↓	↓	Yes	50,000	Yes	11
8	↓	↓	↓	No	↓	Yes	11
9	↓	↓	↓	Yes	↓	No	11
10	↓	↓	↓	No	↓	Yes	11
11	↓	↓	↓	Yes	↓	Yes	11
12	↓	↓	↓	No	↓	No	11

* See BNWL Drawing H-3-15278 for restrictor details and location.

and thermal dam dimensions must be adjusted. The operating conditions and the capsule physical design parameters required to obtain desired temperatures are summarized in Table 2 and Table 3, respectively.

GETR LOCATION

The capsules will be irradiated in GETR pool positions in RAFT facilities possessing unperturbed thermal neutron flux of about 1×10^{14} nvt. The desired maximum power generation is 14.5 kW/ft. This power will be obtained by adjustment of the RAFTs.

SPECIAL FACILITIES

The maximum heat generation rate of 14.5 kW/ft requires irradiation of the capsules in RAFTs. Twelve RAFTs and four temperature recorders mounted in two consoles will be supplied by BNW. These facilities will accommodate all of the capsules in this series.

IRRADIATION REQUIREMENTS

The initial series of capsules requires two burnup levels. The first group of six are to be irradiated to an average burnup of 10,000 MWd/MTM and the second group of six are to be irradiated to an average burnup of 50,000 MWd/MTM. Although burnup levels and burnup times are presented in Table 1, termination of the irradiations will be based upon burnup calculations made as the tests progress.

The desired insertion and withdrawal schedule for the program is presented in Table 4.

TABLE 2. Nominal Operating Conditions

Number of Capsules	12
Maximum Power (kW/ft)	14.5
Maximum Surface Heat Flux (Btu/hr-ft ²)	185,600
Peak Power/Average Power Ratio	1.45/1
Coolant Flow Rate (gpm)	6.55
Coolant Velocity Past Capsule (fps)	9.01
Coolant Pressure Drop Across Capsule (psi) \pm 10%	9.1
Coolant Inlet Temperature ($^{\circ}$ F)	110
Coolant Outlet Temperature ($^{\circ}$ F)	141
Heat Transfer Film Coefficient	3150
Maximum Capsule Wall Temperature ($^{\circ}$ F)	185
Maximum Fuel Cladding Surface Temperature ($^{\circ}$ F)	829
Maximum Fuel Surface Temperature ($^{\circ}$ F)	1808
Maximum Fuel Central Temperature ($^{\circ}$ F)	4046
Maximum Fuel Cladding Thermal Stress (psi)	18,000
Maximum Fuel Cladding Pressure Stress (psi)	8,775
Maximum Capsule Wall Thermal Stress (psi)	16,400
Maximum Capsule Wall Pressure Stress (psi)	1,428

TABLE 3. Principal Capsule Design ParametersFuel75 wt% Natural UO_2 - 25 wt% PuO_2

OD (in.)	0.212
Pellet wt (g/in.)	5.97
Pellet Density (g/cm ³)	9.73
Pellet ²³⁵ U wt (g/in.)	0.028
Pellet ²³⁹ Pu + ²⁴¹ Pu wt (g/in.)	1.214
Pellet Column Length (in.)*	31
Smeared Density (% TD)	88

Depleted Pellets**

OD (in.)	0.214
Length (in.)	0.500
Weight (g/in.)	5.95

Clad Material (304 SS)

OD (in.)	0.250
ID (in.)	0.218
Plenum Volume (in. ³)	0.301

Thermal Dams78/22 NaK

ID (in.)	0.250
OD (in.)	0.340

* In capsules with axial fuel motion restrictors, the UO_2 - PuO_2 fuel column is reduced to 30 1/2 in. long.
(See BNWL Drawing H-3-15278).

** One 1/2 in. long pellet at each end of fuel column.

TABLE 3. (contd)

<u>Aluminum</u>		
ID (in.)		0.340
OD (in.)		0.630
<u>NaK</u>		
ID (in.)		0.630
OD (in.)		0.710
<u>304 SS</u>		
ID (in.)		0.710
OD (in.)		0.947
<u>NaK</u>		
ID (in.)		0.947
OD (in.)		1.027
<u>Outer Containment (304 SS)</u>		
ID (in.)		1.027
OD (in.)		1.125
<u>Capsule Data</u>		
Capsule Length (in.)		65.625
Capsule Weight (g)		
Fuel		0.19
NaK		0.14
Aluminum		0.28
304 SS		3.6

TABLE 4. Desired Capsule Insertion
and Withdrawal Schedule

<u>Cycle Number</u>	<u>Number of Capsules</u>		
	<u>Inserted</u>	<u>Withdrawn</u>	<u>in Reactor</u>
93	+2		2
94	+2		4
95	+2		6
96	+2	-2	6
97	+2	-2	6
98	+2	-2	6
99	-	-	6
100	-	-	6
101	-	-	6
102	-	-	6
103	-	-	6
104	-	-	6
105		-2	4
106		-2	2
107		-2	0

DRAWINGS AND SPECIFICATIONS LIST

DRAWINGS

H-3-27601 (1) GETR-TREAT CAPSULE INNER ASSEMBLY
 (2) GETR-TREAT CAPSULE INNER DETAILS
 (3) GETR-TREAT CAPSULE INNER DETAILS
 H-3-15278 GETR-TREAT CAPSULE FUEL PIN

H-3-27614 EXTENSOMETER
H-3-27795 GETR T-C TERMINAL BOX ARRANGEMENT
H-3-27628 INSTRUMENTATION GETR THERMOCOUPLE TERMINAL
BOX ASSEMBLY

EXPERIMENT DESCRIPTION

DESIGN DESCRIPTION

The basic capsule concept is derived from that used to successfully irradiate mixed oxide fuel specimens in the GETR for Task C of the Fast Ceramic Reactor Development Program (PA 10).

The capsule is approximately 65-3/16 in. long by 1-1/8 in. diameter. A 1/4 in. diameter fuel pin is positioned in the bottom 49 in. of the capsule. NaK-bonded aluminum and stainless steel thermal dams are used to achieve the required cladding temperatures. Spacing and concentricity of the thermal dams is maintained by centering lugs on the outer surfaces of the dams.

The fuel pins not provided with axial fuel motion restrictors contain 31 in. of mechanically blended - mixed oxide (75% UO_2 - 25% PuO_2) fuel pellets and a 1/2-in. depleted UO_2 pellet at each end of the fuel column. At the top of the fuel column is a 5-in. long nickel reflector and an extensometer to measure maximum axial fuel expansion. A gas plenum is included to accommodate fission gas release without excessively stressing the cladding. An aluminum - 0.1% cobalt flux wire encapsulated in 0.040 in. diameter stainless steel tubing is used to simulate the spiral wire wrap of a prototypic fuel pin.

The fuel pins containing axial fuel motion restrictors are identical to those without restrictors except that two 1/4-in. long fuel pellets are replaced by restrictors. The restrictor design and material selection will be based on a series of

screening tests conducted in the hydraulic rabbit facility in the MTR. These tests are to evaluate short-term compatibility of the restrictor materials with molten fuel and their effectiveness in preventing or controlling axial motion of molten fuel.

INSTRUMENTATION

Temperature

Each of the capsules is instrumented with six chromel-alumel, stainless steel-sheathed, grounded-junction thermocouples. The thermocouples are located in two of the three NaK annuli. The thermocouples will provide NaK temperature data for various locations in the capsules. These data will be used to control the position of the capsules and thus the fuel specimen heat generation rate.

Temperatures will be recorded on standard 0-1500 °F, 12-in. strip chart, K-calibrated, 12-point recorders. The four recorders to be furnished by PNL will accommodate all of the thermocouples. The recorders, each of which will accommodate two capsules, will be equipped with high temperature alarms and an up-scale burnout feature.

Flow

The RAFTs to be used for the irradiations will be supplied with water from the auxiliary capsule header. Calculated flow rates are more than adequate for safe heat removal.

IRRADIATION FACILITIES

The capsules are to be irradiated in radially adjustable facility tubes. Twelve such facilities are required. The RAFTs will be fabricated by PNL.

DESIGN ANALYSIS SUMMARY

The design analysis is summarized in the following, while the detailed design analysis is presented in the Appendix.

HEAT TRANSFER ANALYSIS

Capsule designs and operating conditions were selected to obtain a maximum outer containment surface temperature of less than 220 °F and a maximum surface heat flux of less than 2/3 burnout heat flux. Maximum surface temperature at 14.5 kW/ft peak power is 184 °F.

HYDRAULICS ANALYSIS

The hydraulics analysis indicates that the required flow rate of 6.55 gpm can be obtained with a 9.1 psi pressure drop across the capsule. This pressure drop is easily attainable from the auxiliary capsule header pressure. The minimum flow set point should be 4.5 gpm. At this flow rate, capsule wall burnout condition will not be reached and the $\text{UO}_2\text{-PuO}_2$ fuel will not become molten, even at a 25% overpower condition.

STRESS ANALYSIS

Fuel Pin

Assuming the collection of all fission gases in the plenum, a plenum temperature of 200 °F, and 100% release of all absorbed and fission gases, the maximum internal pressure at operating temperature in any of the capsules after 50,000 MWd/MTM average burnup will be 89 atmospheres. The corresponding sheath hoop stress is 8,775 psi. All of the assumptions are conservative and the actual pressure is expected to be considerably less.

Combining the maximum thermal stress in the clad with the maximum pressure stress in accordance with methods delineated by ASME Pressure Vessel Code indicates that the maximum stress will not exceed safe limits. Summaries of the maximum stress conditions and the maximum design limits are included in the stress analysis.

Outer Containment

Pressure will build up in the outer containment plenum as a result of NaK expansion at operating temperature. Under normal operating conditions, this pressure of approximately 2.7 atm corresponds to a hoop stress of 419 psi.

A fuel pin failure at the end of 50,000 MWd/MTM burnup would increase the pressure in the outer containment to approximately 9 atm. This pressure corresponds to a hoop stress of 1453 psi. ASME Pressure Vessel Code methods indicate that the outer container can adequately contain the released gases, even for penetrations of only 50% in the closure welds.

HAZARDS

The hazards involved in these irradiations are those associated with NaK filled-plutonium fueled capsules. Comparable experiments have been performed in GETR without operating or safety difficulties (Ref-FCR-PA 10 Experiments). All capsule component materials confirm to ASTM specifications and were selected for use through NDT inspections. All containment welds were X-radiographed and helium leak tested (1×10^{-10} cm³/sec sensitivity) during fabrication to assure leaktight closures.

The possibility of discharging NaK or plutonium to the reactor pool is remote as evidenced by extensive past experience with capsules of this design. This experience includes at least one failure of the fuel specimen cladding (Capsule C3D of the PA-10 program).

SHIPPING AND HANDLING

HANDLING

All handling and movements of capsule will be performed with capsules in the vertical position. The sponsor must be notified at any time verticality is disturbed by more than 20°

SHIPPING

The capsules will be shipped to and from the reactor site in special shipping containers in which the capsules will be positioned vertically. These containers will be supplied by PNL.

THERMOCOUPLE INSTALLATION

GENERAL INSTRUCTIONS

Thermocouple lead final connections will be made at the reactor site. Final closure of the lead system will be accomplished by TIG welding. The closure will be leak-tested to assure adequate closure. All thermocouples will be checked for resistance and continuity before and after making the final connections. The resistance measurements should be compared with those accompanying the capsules.

SPECIFIC INSTRUCTIONS

- Keep capsule vertical
- Measure thermocouple resistances and check values against those accompanying capsules.
- Connect Parts 25 and 26, Dwg H-3-27601 (1).
- Fusion weld Part 13 to Part 23 per Note 6 on Dwg H-3-27601(1)
- Helium leak test weld to conform with Note 4 on Dwg H-3-27601 (1).
- Make T-C lead wire connections in junction box per Dwg H-3-27795.
- Connect T-C leads at the consoles so that T-C's 1 through 6 for each capsule will print in numerical sequence 1 through 6; 7 through 12, etc.

CAPSULE INSTALLATION

- Keep capsules vertical at all times.
- Inspect capsules and lead tubes for any sign of damage. Should the capsules be subjected to any significant shock prior to installation, the test engineer and the sponsor are to be notified before proceeding further.

- Inspect facility tubes and the radial mechanisms. Any observed malfunctions should be reported to the responsible test engineer.
- After a final thermocouple check, carefully install the capsule in the facility tube.
- Perform functional checks of radially adjusting mechanisms. Determine actual distance from facility tube to the reactor vessel and calibrate the scale on adjusting mechanism. The distance from the facility tube to the vessel is to be measured at the top, center, and bottom of the facility tube.
- Perform a continuity and resistance check on all thermocouples. These data should be compared with those obtained earlier.
- All tests should be performed to the satisfaction of the test engineer and the test sponsor prior to startup.

OPERATION

NORMAL OPERATION AND CAPSULE POSITION

The capsules are to be repositioned radially during irradiation to maintain the required experimental power. The capsules are to operate at a maximum power of 14.5 kW/ft. Power level will be determined by the capsule internal temperatures as indicated by the thermocouples.

The RAFTs will be full out prior to and during startup. After the reactor has reached full power, the RAFTs will be moved in steps toward the core until the required operating conditions are achieved. Capsule position should be maintained for a minimum of 10 min after each radial movement to allow capsule temperatures to equilibrate for reading accuracy.

EXPECTED THERMOCOUPLE READINGS

Internal capsule temperatures, as measured from the thermocouples, will be used to adjust the capsule positions. Expected

thermocouple readings at 14.5 kW/ft for rod banks from 18.6 in. to 27.8 in. are presented in Table 5 and plotted in Figure 1.

TABLE 5. Expected Thermocouple Readings for Capsules PNL-59-1 through 59-12 (at 14.5 kW/ft)

<u>T/C No.</u>	<u>Position</u>	<u>Temperature, °F, for Rod Bank Height of:</u>			
		<u>18.6 in.</u>	<u>23.0 in.</u>	<u>25.8 in.</u>	<u>27.8 in.</u>
1	Lower Inner	598	578	543	514
2	Lower Outer	274	267	256	246
3	Center Inner	594	672	707	710
4	Center Outer	282	307	318	319
5	Upper Inner	323	386	461	522
6	Upper Outer	203	224	245	263

All indicated temperatures in any capsule exceeding the expected temperatures by a uniform amount would suggest a probable overpower condition. The RAFT should be backed out until the expected temperatures are obtained or until the cause of the high temperatures is confirmed and corrected. Figure 2 shows the allowable temperature range of thermocouple No. 3 at the required power ratings. Thermocouple No. 3 will be used as a control guide for positioning the capsules during irradiation. Thermocouple No. 1 will be the alternate control thermocouple. Figure 3 shows the allowable temperature range of Thermocouple No. 1

The radial temperature drop from the inner to the outer thermocouples versus rod bank at a power of 14.5 kW/ft is shown in Figure 4. Figure 5 shows peak rod power versus Thermocouple No. 3 readings at various rod banks.

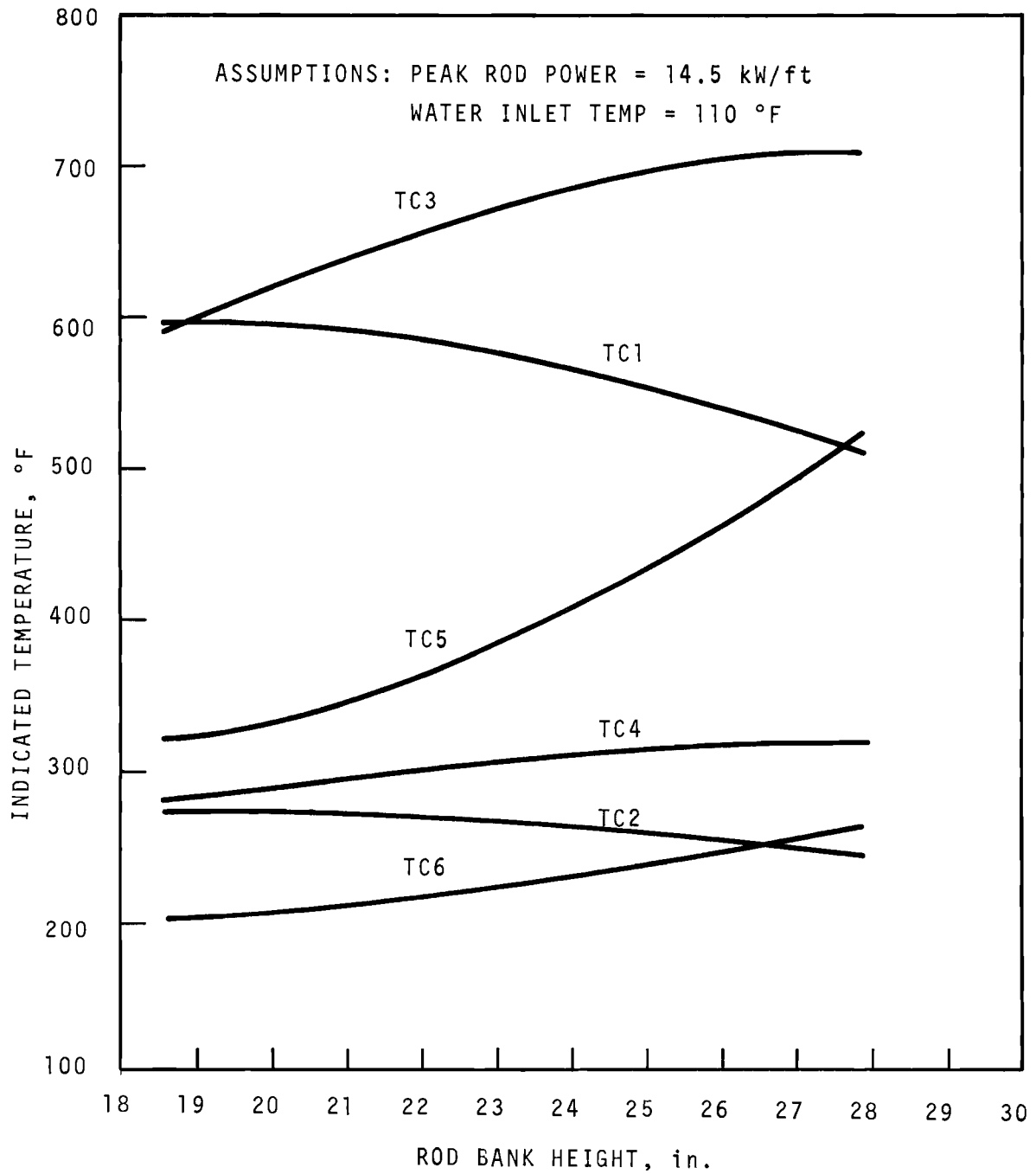


FIGURE 1. Expected Thermocouple Readings
for Capsules PNL 59-1 through 59-12

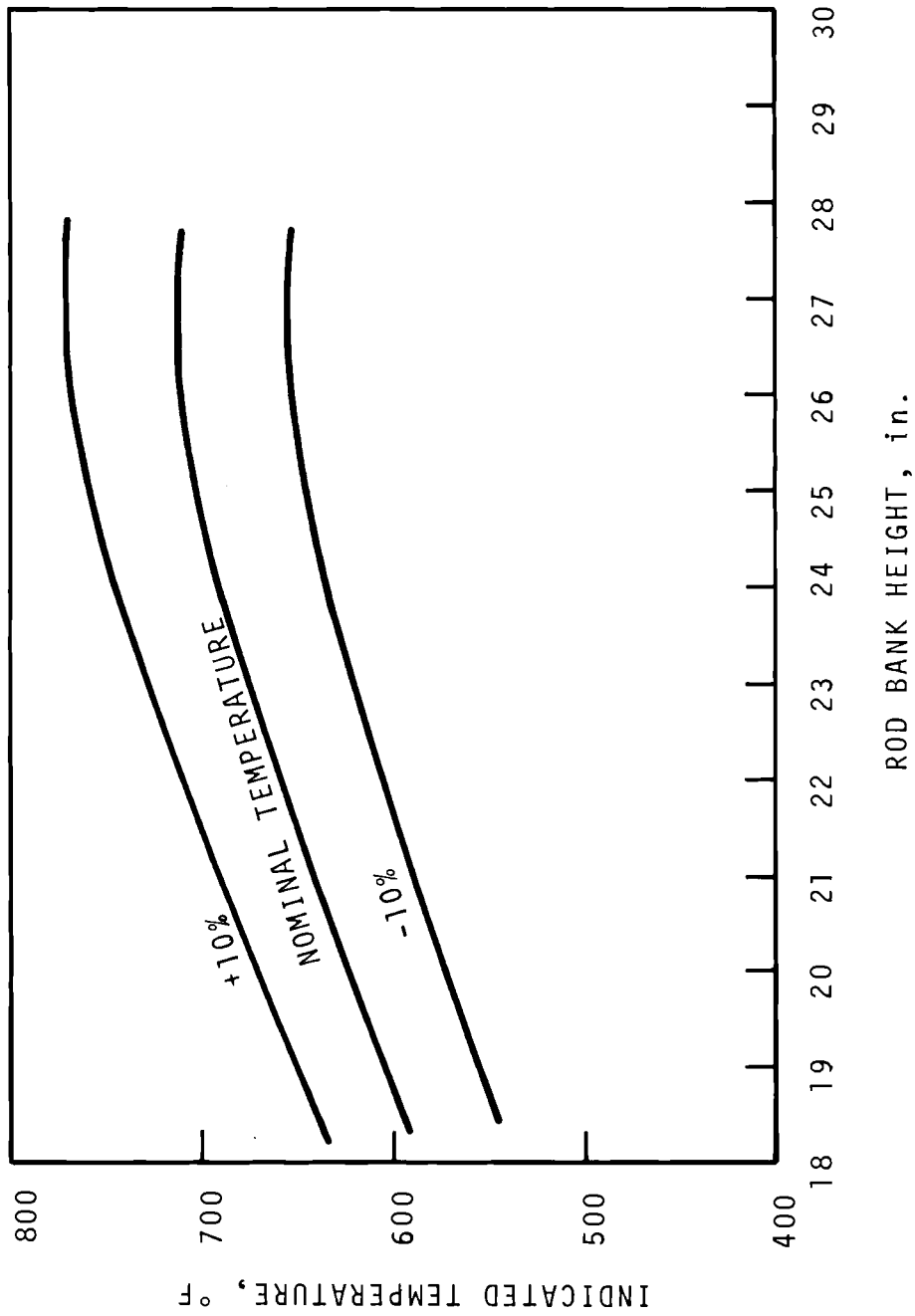


FIGURE 2. Thermocouple No. 3 Indicated Temperature Versus Rod Bank Position for PNL 59-1 through PNL 59-12

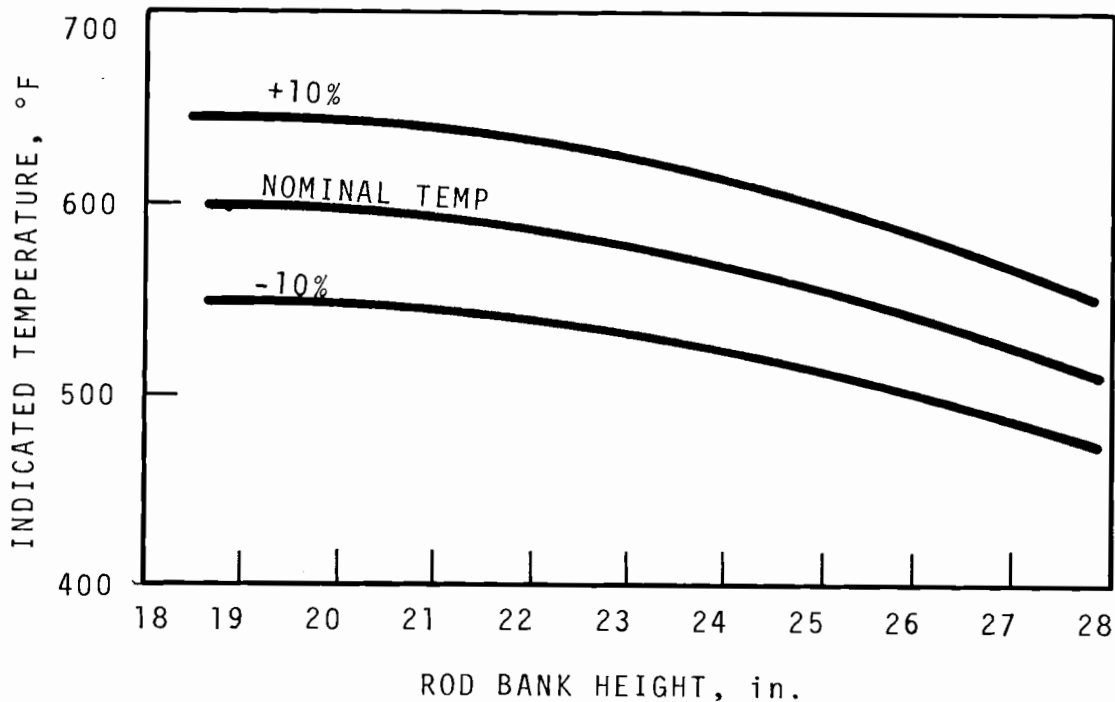


FIGURE 3. Thermocouple No. 1 (alternate control)
Indicated Temperature Versus Rod Bank
Position for PNL 59-1 through PNL 59-12

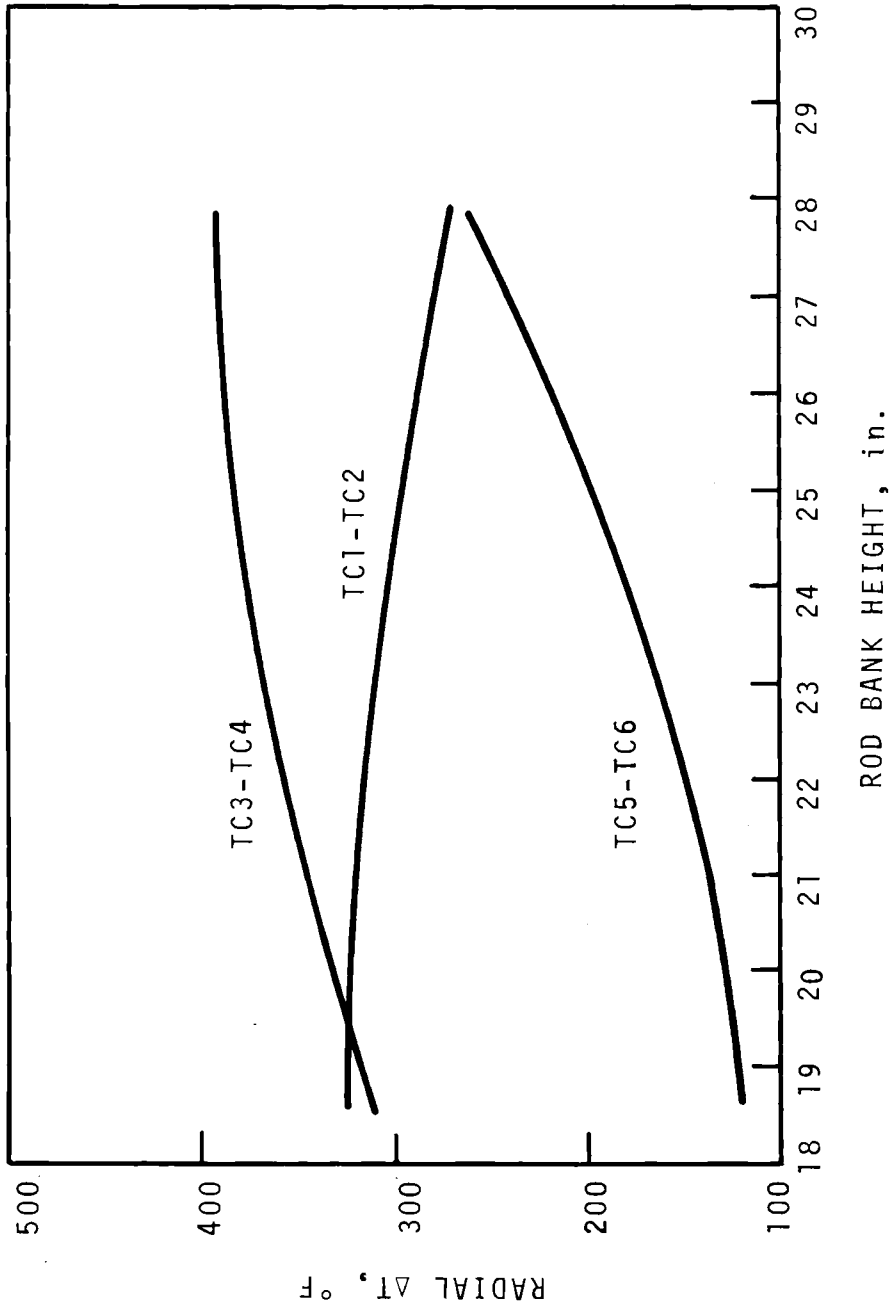


FIGURE 4. Radial Temperature Drop from Inner to Outer Thermocouple at Design Power of 14.5 kW/ft

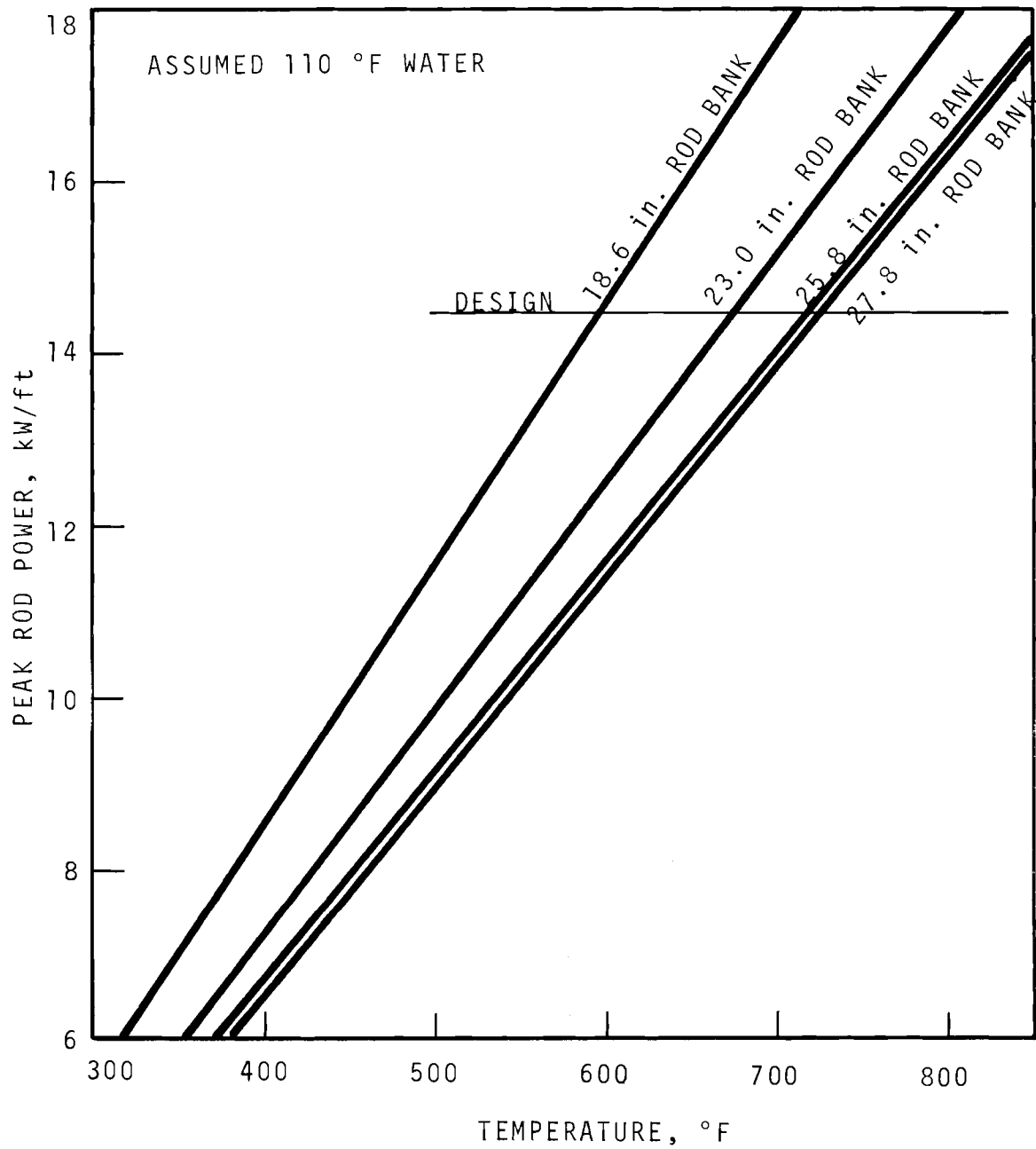


FIGURE 5. Peak Rod Power Versus Thermocouple No. 3 Temperature

DATA

Standard GETR data sheets should be used for the collection of data and, in addition to the recorder strip charts, the test sponsor should be supplied with the following:

- Reactor power level
- Rod bank
- Equivalent full power days of operation
- Raft position changes

OPERATIONAL FAILURES AND WITHDRAWAL CONDITIONSThermocouple Failure

Since the capsule temperatures will be the primary control basis during these tests, any indication of T-C failure should be reported to the test engineer as soon as possible. Failure of too many thermocouples could preclude testing.

RAFT Failure

The test should not be significantly disturbed by the development of functional difficulties in positioning devices. The test sponsor should be notified of any malfunctions prior to discharging of any test capsules.

Fuel Element Failure

A sudden change in temperature registered by all of the thermocouples in a capsule may be attributed to a change in power, a change in coolant flow, or a capsule failure.

Capsule failure would probably occur by one of the following mechanisms: (1) NaK discharged to coolant, (2) NaK and fuel discharged to coolant, or (3) fuel discharged to the NaK reservoir.

Although a failure is unlikely, any capsule removed because of a suspected failure should be handled with care. The sponsor should be notified of any suspected failure as soon as possible. If nondestructive examination of a suspected failure fails to disclose a defect, the capsule will be reinserted for additional irradiation.

APPENDIX
CALCULATIONS

NOMENCLATURE

A	= Area
D_e	= Equivalent Diameter
E	= Modulus of Elasticity
f	= Friction Factor
g	= Gravitational Acceleration
h_f	= Coolant Film Coefficient
h_i	= Fuel-Clad Interface Coefficient
K	= Thermal Conductivity
L	= Length
MT	= Metric Ton
N	= Number of atoms
P	= Pressure
Q_γ	= Gamma Heat
Q'	= Heat Generation Rate
Q''	= Surface Heat Flux
S_y	= Yield Strength
T	= Temperature
μ	= Poissons Ratio
V	= Volume
v	= Velocity
W	= Mass Flow Rate
α	= Coefficient of Thermal Expansion
ρ	= Density
σ_H	= Hoop Stress
σ_{th}	= Thermal Stress

APPENDIX
CALCULATIONS

I. CAPSULE SURFACE HEAT FLUX

A. Power Generation

Capsules PNL 59-1 through PNL 59-12 (solid pellet fuel specimens) will be irradiated in the GETR pool in RAFT facilities so that a maximum power generation of 14.5 kW/ft will be maintained.⁽¹⁾ The facility tubes will be moved closer to the core as required to maintain the power level during irradiation.

$$Q' = 14.5 \text{ kW/ft}$$

B. Fission Heat

$$\begin{aligned} Q' &= 14.5 \text{ kW/ft} \times 3413 \text{ Btu/kW hr} \\ &= 49,489 \text{ Btu/hr-ft} \end{aligned}$$

C. Gamma Heating @ 1.6 watts/gm = 2480 Btu/hr-lb.

where:

$$\rho_{\text{NaK}} = 0.0313 \text{ lb/in}^3$$

$$\rho_{\text{Al}} = 0.0976 \text{ lb/in}^3$$

$$\rho_{\text{SS}} = 0.286 \text{ lb/in}^3$$

$$\begin{aligned} Q_{\gamma 3}^* &= \frac{\pi}{4} (0.340^2 - 0.250^2) \times \frac{12 \text{ in.}}{\text{ft}} \times \frac{0.0313 \text{ lb}}{\text{in}^3} \times \frac{2480 \text{ Btu}}{\text{hr-lb}} \\ &= 38.8 \text{ Btu/hr-ft} \end{aligned}$$

$$\begin{aligned} Q_{\gamma 4} &= \frac{\pi}{4} (0.630^2 - 0.340^2) \times 12 \times 0.0976 \times 2480 \\ &= 644 \text{ Btu/hr-ft} \end{aligned}$$

*See Figure A-1 for zone identification.

$$\begin{aligned}
 {}_4Q'_{\gamma 5} &= \frac{\pi}{4} (0.710^2 - 0.630^2) \times 12 \times 0.0313 \times 2480 \\
 &= 89.3 \text{ Btu/hr-ft}
 \end{aligned}$$

$$\begin{aligned}
 {}_5Q'_{\gamma 6} &= \frac{\pi}{4} (9.947^2 - 0.710^2) \times 12 \times 0.286 \times 2480 \\
 &= 2940 \text{ Btu/hr-ft}
 \end{aligned}$$

$$\begin{aligned}
 {}_6Q'_{\gamma 7} &= \frac{\pi}{4} (1.027^2 - 0.947^2) \times 12 \times 0.0313 \times 2480 \\
 &= 197.0 \text{ Btu/hr-ft}
 \end{aligned}$$

$$\begin{aligned}
 {}_7Q'_{\gamma 8} &= \frac{\pi}{4} (1.125^2 - 1.027^2) \times 12 \times 0.286 \times 2480 \\
 &= 1420 \text{ Btu/hr-ft}
 \end{aligned}$$

D. Total Linear Heat Generation Rate

$${}_1Q'_2 = 49,489 \text{ Btu/hr-ft}$$

$${}_2Q'_3 = 49,489 + 39 = 49,528 \text{ Btu/hr-ft}$$

$${}_3Q'_4 = 49,528 + 644 = 50,172 \text{ Btu/hr-ft}$$

$${}_4Q'_5 = 50,172 + 89 = 50,261 \text{ Btu/hr-ft}$$

$${}_5Q'_6 = 50,261 + 2940 = 53,201 \text{ Btu/hr-ft}$$

$${}_6Q'_7 = 53,201 + 107 = 53,308 \text{ Btu/hr-ft}$$

$${}_7Q'_8 = 53,308 + 1420 = 54,728 \text{ Btu/hr-ft}$$

E. Capsule Surface Heat Flux

$$Q''_{\max} = \frac{54,728 \text{ Btu/hr-ft} \times 12 \text{ in/ft}}{\pi (1.125) \text{ in.}}$$

$$= 185,600 \text{ Btu/hr-ft}^2$$

II. COOLANT CONDITIONSA. Flow Area (A_F)

Capsule O.D. 1.125 in.

Coolant Channel I.D. = 1.250 in.

$$A_F = \pi(1.250^2 - 1.125^2)/4$$

$$= 0.233 \text{ in}^2 = 0.00162 \text{ ft}^2$$

B. Water Velocity (v)

Requested water flow rate = 6.55 gpm = 3210 lb/hr.

$$v = (6.55 \text{ gal/min}) (1/0.00162 \text{ ft}^2) (\text{ft}^2/7.481 \text{ gal}) (1 \text{ min}/60 \text{ sec})$$

$$= 9.01 \text{ ft/sec}$$

C. Bulk Coolant Temperature Rise (ΔT_B)

where:

$$\text{Peak Power}/\text{Av Power} = 1.45$$

$$\text{Coolant Inlet Temp} = 110 \text{ }^\circ\text{F}$$

$$\text{Heat Transfer Area } (A_H) = 0.761 \text{ ft}^2$$

$$\text{Mass Flow Rate } (W) = 3210 \text{ lb/hr}$$

$$(\Delta T_B) = \frac{185,600 \text{ Btu}}{\text{hr} \cdot \text{ft}} \times 0.761 \text{ ft}^2 \times \frac{\text{hr}}{32.0 \text{ lb.}} \times \frac{\text{lb } ^\circ\text{F}}{\text{Btu}} \times \frac{1}{1.45}$$

$$= 31 \text{ }^\circ\text{F}$$

$$\text{Coolant Outlet Temperature} = 110 + 31 = 141 \text{ }^\circ\text{F}$$

D. Temp Drop Across Film (ΔT_f)

$$\Delta T_f = Q''/h_f$$

$$h_f = 170 (1 + t \times 10^{-2} - t^2 \times 10^{-5}) v^{0.8} / D_e^{0.2} \quad (2)$$

$$t = (110 + 141)/2 = 125.5 \text{ } ^\circ\text{F}$$

$$v^{0.8} = (9.01)^{0.8} = 5.8$$

$$D_e^{0.2} = (0.125)^{0.2} = 0.66$$

$$\begin{aligned} h_f &= 170 (1 + 1.255 - 0.1578) 5.8 / 0.66 \\ &= 3150 \end{aligned}$$

$$\Delta T_f = 185,600 / 3156 = 59 \text{ } ^\circ\text{F}$$

E. Capsule Surface Temperature (T_s)

$$T_s = 126 + 59 = 185 \text{ } ^\circ\text{F}$$

where 126 $^\circ\text{F}$ = bulk temp. at peak power position for cycle average flux condition.

F. Pressure Drop Across Fuel Element

Assume coolant channel is 4 ft long

Assume commercial pipe friction factors

$$\Delta P = \frac{f L \rho v^2}{2 g D_e} \quad (3)$$

$$\text{where: } f = 0.044$$

$$L = 4 \text{ ft}$$

$$\rho = 61 \text{ lb/ft}^3$$

$$v^2 = (9.01)^2 = 81.5 \text{ ft}^2/\text{sec}^2$$

$$g = 32.2 \text{ ft/sec}^2$$

$$D_e = 0.0104 \text{ ft}$$

$$\Delta P = \frac{(0.044) (4) (61) (81.5)}{(64.4) (0.0104) (144)} = 9.1 \text{ psi}$$

G. Burnout Heat Flux (4)

$$(Q'')_{B.O.} = h_{B.O.} (T_w - T_b)_{B.O.}$$

1. Burnout Wall Temp. ($T_{w.B.O.}$)

$$T_{w.B.O.} = 1.8 \left[57(\ln P) - 54 \left(\frac{P}{P + 15} \right) - \frac{v}{4} \right] + 32$$

where:

$$v = 9.01 \text{ ft/sec}$$

$$P = 20 \text{ psig} \approx 34 \text{ psia}$$

$$\begin{aligned} T_{w.B.O.} &= 1.8 \left[(57)(3.53) - 54 \left(\frac{34}{49} \right) - \frac{9}{4} \right] + 32 \\ &= 1.8 [201 - 37.5 - 2.24] + 32 \\ &= 291 + 32 = 323 \text{ }^\circ\text{F} \end{aligned}$$

2. Film Coefficient ($h_{B.O.}$)

$$h_{B.O.} = 10,890 \left(\frac{D_e}{D_e + D_i} \right) + \text{Slope } v$$

where:

$$D_i = (1.125 \text{ in}) (1 \text{ ft}/12 \text{ in}) = 0.094 \text{ ft}$$

$$D_e = 0.0104 \text{ ft.}$$

$$\text{Slope} = 48/(D_e)^{0.6} = 742$$

$$v = 9.01 \text{ ft/sec}$$

$$\begin{aligned} h_{B.O.} &= 10,890 \left(\frac{0.0104}{0.0104 + 0.094} \right) + 742(9) \\ &= 1083 + 6680 = 7763 \end{aligned}$$

3. Burnout Heat Flux*

$$(Q'')_{B.O.} = h_{B.O.} (T_{w.B.O.} - T_b)_{B.O.}$$

where:

$$T_b = (110 + 141)/2 = 126 \text{ } ^\circ\text{F}$$

$$\begin{aligned} (Q'')_{B.O.} &= 7763 (323-126) \\ &= 1,530,000 \text{ Btu/hr-ft}^2 \end{aligned}$$

4. Critical Heat Flux

$$\begin{aligned} (Q'')_{crit} &= 0.6 (1.53 \times 10^6) \\ &= 918,000 \text{ Btu/hr-ft}^2 \end{aligned}$$

H. Minimum Flow

1. Assume $v = 6 \text{ ft/sec}$ (Flow rate = 4.37 gpm)

a. Burnout Wall Temp ($T_{w.B.O.}$)

$$P = 20 \text{ psig} = 34 \text{ psia}$$

$$\begin{aligned} T_{w.B.O.} &= 1.8 [201 - 37.5 - 6/4] + 32 \\ &= 292 + 32 = 324 \text{ } ^\circ\text{F} \end{aligned}$$

b. Film Coefficient ($h_{B.O.}$)

$$\begin{aligned} h_{B.O.} &= 1083 + (742)(6) \\ &= 5553 \end{aligned}$$

c. Burnout Heat Flux

$$\text{where: } \Delta T_b = 31 \text{ } ^\circ\text{F} (9 \text{ ft/sec}) / (6 \text{ ft/sec}) = 470 \text{ } ^\circ\text{F}$$

$$T_b = (110 \text{ } ^\circ\text{F} + 157 \text{ } ^\circ\text{F}) / 2 = 134 \text{ } ^\circ\text{F}$$

$$\begin{aligned} (Q'')_{B.O.} &= 5553 (324-134) \\ &= 1,055,000 \text{ Btu/hr-ft}^2 \end{aligned}$$

*See Figure A-2 for Critical Heat Flux versus Flow Rate.

d. Critical Heat Flux (Q'')_{crit.}
 (Q'') _{crit} $0.6(1,055,000)$
 $= 632,000 \text{ Btu/hr-ft}^2$

2. Assume $v = 3 \text{ ft/sec}$ (Flow rate = 2.18 gpm)

a. Burnout Wall Temp. ($T_{w.B.O.}$)

$$P = 34 \text{ psi}$$

$$T_{w.B.O.} = 324.5 \text{ }^\circ\text{F}$$

b. Film Coefficient

$$h_{B.O.} = 1083 + (742)(3) = 3308$$

c. Burnout Heat Flux

where:

$$\Delta T_b = 31 (9/3) = 93 \text{ }^\circ\text{F}$$

$$T_b = (110 + 203)/2 = 157 \text{ }^\circ\text{F}$$

$$(Q'')$$
_{B.O.} $= 3308 (324.5 - 157)$

$$= 554,000 \text{ Btu/hr-ft}^2$$

d. Critical Heat Flux

$$0.6 (Q'')$$
_{B.O.} $= 333,000 \text{ Btu/hr-ft}^2$

e. Surface Heat Flux at 25% Overpower

$$Q'' = (125) (185,600 \text{ Btu/hr-ft}^2)$$

$$= 232,000 \text{ Btu/hr-ft}^2$$

f. Surface Heat Flux at Molten Fuel Condition

$$Q'' = (185,600 \text{ Btu/hr-ft}^2) (20 \text{ kW/ft}) / (14.5 \text{ kW/ft})$$

$$= 255,000 \text{ Btu/hr-ft}^2$$

III. THERMAL CONDITIONS

A. Temperature Drop Through Element

$$\Delta T = \frac{Q' \ln(D_o/D_i)}{2\pi K}$$

where

$$K_{Al} = 100 \text{ Btu/hr-ft-}^\circ\text{F}$$

$$K_{NaK} \text{ (See Figure A-3)}$$

$$K_{304} = \text{(See Figure A-4)}$$

$$7\Delta T_8^* = \frac{54,728 \text{ Btu/hr-ft}}{2\pi \times 9.6 \text{ Btu/hr-ft }^\circ\text{F}} \left(\ln \frac{1.125}{1.027} \right) = 83 \text{ }^\circ\text{F}$$

$$6\Delta T_7 = \frac{53,308}{2\pi \times 13.5} \left(\ln \frac{1.027}{0.947} \right) = 53 \text{ }^\circ\text{F}$$

$$5\Delta T_6 = \frac{53,201}{2\pi \times 10.4} \left(\ln \frac{0.947}{0.710} \right) = 234 \text{ }^\circ\text{F}$$

$$4\Delta T_5 = \frac{50,261}{2\pi \times 15} \left(\ln \frac{0.710}{0.630} \right) = 63 \text{ }^\circ\text{F}$$

$$3\Delta T_4 = \frac{50,172}{2\pi \times 100} \left(\ln \frac{0.630}{0.340} \right) = 49 \text{ }^\circ\text{F}$$

$$2\Delta T_3 = \frac{49,528}{2\pi \times 15.1} \left(\ln \frac{0.340}{0.250} \right) = 161 \text{ }^\circ\text{F}$$

$$1\Delta T_2 = \frac{49,489}{2\pi \times 12.2} \left(\ln \frac{0.250}{0.218} \right) = 88 \text{ }^\circ\text{F}$$

*See Figure A-1 for zone identification.

B. Capsule Temperatures

$$T_8 = 185 \text{ }^\circ\text{F}$$

$$T_7 = 185 + 83 = 268 \text{ }^\circ\text{F}$$

$$T_6 = 268 + 53 = 321 \text{ }^\circ\text{F}$$

$$T_5 = 321 + 234 = 555 \text{ }^\circ\text{F}$$

$$T_4 = 555 + 63 = 618 \text{ }^\circ\text{F}$$

$$T_3 = 618 + 49 = 667 \text{ }^\circ\text{F}$$

$$T_2 = 667 + 161 = 829 \text{ }^\circ\text{F}$$

$$T_1 = 829 + 88 = 917 \text{ }^\circ\text{F}$$

C. Fuel Temperature1 - Fuel Surface Temperature

$$T_{f.s.} = T_1 + \Delta T_i$$

$$(5) h_i = 1000 \text{ Btu/hr-ft}^2 \cdot \text{ }^\circ\text{F}$$

$$\Delta T_i = \frac{(49,489 \text{ Btu/hr-ft})(12 \text{ in/ft})}{(\pi \times 0.212 \text{ in.})(1000 \text{ Btu/hr-ft}^2 \cdot \text{ }^\circ\text{F})}$$

$$\Delta T_i = 892 \text{ }^\circ\text{F}$$

$$T_{f.s.} = 916 + 892 = 1808 \text{ }^\circ\text{F}$$

D. Fuel Central Temperature⁽⁵⁾

$$\frac{\phi_c}{\phi_s} = 0.33 \text{ for solid pellet}$$

$$F = 0.735$$

$$\begin{aligned} \int_{T_s}^{T_c} K dt &= \frac{Q'}{4\pi} F \\ &= \frac{49,489}{4\pi} (0.735) \\ &= 2890 \text{ Btu/hr-ft} \\ &= 27.8 \text{ w/cm} \end{aligned}$$

$$\int_0^{T_s} K dt = 25.2 \text{ w/cm}$$

$$\int_0^{T_c} K dt = 25.2 \text{ w/cm} + 27.8 \text{ w/cm} = 53 \text{ w/cm}$$

$$T_c = 2230 \text{ }^\circ\text{C} = 4046 \text{ }^\circ\text{F} \text{ (See Figure A-5)}$$

IV. STRESS ANALYSISA. Thermal Expansion (See Figure A-6)

where:*

$$\gamma_{(ss)_e} = 9.2 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_{(ss)_e} = 9.7 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_{A_4} = 13.1 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_{ss_2} = 10.7 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_{NaK} = 1.62 \times 10^{-4} \text{ ft}^3/\text{ft}^3/^\circ\text{F} \text{ (calculated from } \rho \text{ values in Figure A-7)}$$

1. Outer Tube (6-7)

$$\begin{aligned} \Delta L &= (31 \text{ in})(9.2 \times 10^{-6} \text{ in/in/}^\circ\text{F}) \left(\frac{184 + 267}{2} - 70 \right) \\ &= 0.0491 \text{ in.} \end{aligned}$$

$$\begin{aligned} \Delta V &= (0.491) \left[\pi(1.125^2 - 1.027^2)/4 \right] \\ &= 0.00813 \text{ in}^3 \end{aligned}$$

2. S/S Thermal Dam (5-8)

$$\begin{aligned} \Delta L &= (31)(9.7 \times 10^{-6}) \left(\frac{554 + 320}{2} - 70 \right) \\ &= 0.106 \text{ in.} \end{aligned}$$

$$\begin{aligned} \Delta V &= (0.106) \left[\pi(0.947^2 - 0.710^2)/4 \right] \\ &= 0.0327 \text{ in}^3 \end{aligned}$$

*See Figure A-1 for zone identification.

Thermal Expansion (Cont'd)3. Al Thermal Dam (3-4)

$$\begin{aligned}\Delta L &= (31)(13.1 \times 10^{-6}) \left(\frac{566 + 617}{2} - 70 \right) \\ &= 0.227 \text{ in.}\end{aligned}$$

$$\begin{aligned}\Delta V &= (0.227) \left[\pi (0.630)^2 - (0.340)^2 / 4 \right] \\ &= 0.0501 \text{ in}^3\end{aligned}$$

4. Fuel Tube (1-2)

$$\begin{aligned}\Delta L &= (31)(10.7 \times 10^{-6}) \left(\frac{916 + 828}{2} - 70 \right) \\ &= 0.264 \text{ in.}\end{aligned}$$

$$\begin{aligned}\Delta V &= (0.264) \left[\pi (0.250)^2 / 4 \right] \\ &= 0.0129 \text{ in}^3\end{aligned}$$

5. NaK Expansion

where:

$$V_1 = 9.52 \text{ in}^3 = 0.0055 \text{ ft}^3$$

$$T_{AV} = 450 \text{ }^\circ\text{F}$$

$$\begin{aligned}\Delta V &= \frac{1.62 \times 10^{-4} \text{ ft}^3}{\text{ft}^3 - \text{ }^\circ\text{F}} (0.0055 \text{ ft}^3)(450-70) \\ &= 0.0003386 \text{ ft}^3 = 0.585 \text{ in}^3\end{aligned}$$

Thermal Expansion (Cont'd)6. Final NaK Volume

$$\begin{aligned}
 V_2 &= V_1 + \Delta V \\
 &= 9.52 \text{ in}^3 + 0.585 \text{ in}^3 \\
 &= 10.11 \text{ in}^3
 \end{aligned}$$

7. Total NaK Cavity Volume

$$V_2 = V_1 + \Sigma \Delta V$$

$$\text{where } V_1 = 17.27 \text{ in}^3$$

$$\begin{aligned}
 V_2 &= 17.27 \text{ in}^3 + 0.00814 \text{ in}^3 - (0.0327 + 0.0501 + 0.0129) \text{ in}^3 \\
 &= 17.18 \text{ in}^3
 \end{aligned}$$

8. Fuel Pin Plenum Volume

$$V_2 = V_1 + \Delta V$$

where

$$V_1 = 0.301 \text{ in}^3$$

Fuel Axial Expansion = 3%

$$\begin{aligned}
 V_2 &= 0.301 \text{ in}^3 + \frac{\pi}{4} (218)^2 (0.264 - 32 \times 0.03) \\
 &= 0.275 \text{ in}^3
 \end{aligned}$$

B. Fuel Rod Internal Pressure1. Fission Gas Pressure

where:

$$\text{Fission Energy} = 200 \text{ Mev/f}$$

Capsule contains 163×10^{-6} MT fissile material

$$1 \text{ Mev} = 5.3916 \times 10^{23} \text{ MWD}$$

$$\text{Av. Burnup} = 50,000 \text{ MWd/MTM}$$

Assume 100% gas release

$$\begin{aligned} N_f &= (5.0 \times 10^4) (1.63 \times 10^{-4}) (1/200) (5.3916 \times 10^{23}) \\ &= 2.097 \times 10^{22} \text{ atoms} \end{aligned}$$

In a thermal flux 32% of fissions from gas ⁽⁶⁾

$$N_g = 0.32 \times 2.097 \times 10^{22} = 7.03 \times 10^{21} \text{ atoms.}$$

$$\begin{aligned} V_g &= \frac{(7.03 \times 10^{21})(2.24 \times 10^4)}{6.023 \times 10^{23}} \\ &= 261 \text{ cm}^3 = 16.0 \text{ in}^3 \text{ (STP)} \end{aligned}$$

Fission Gas Pressure (Cont'd)

Pressure will increase to:

$$P_2 = P_1 \frac{V_1}{V_2} \cdot \frac{T_2}{T_1} \cdot \frac{n_2}{n_1}$$

where:

$$P_1 = 1 \text{ atm.}$$

$$V_1 = 0.301 \text{ in}^3$$

$$T_1 = 70 + 460 = 530 \text{ }^\circ\text{R}$$

$$n_1 = 0.301 \text{ (STP)}$$

$$V_2 = 0.275 \text{ in}^3$$

$$*T_2 = 200 + 460 = 660 \text{ }^\circ\text{R}$$

$$n_2 = 0.301 + 16.0 = 16.301$$

$$P_2 = 1 \text{ atm} \left(\frac{0.301}{0.275} \right) \left(\frac{660}{530} \right) \left(\frac{16.301}{0.301} \right)$$

$$= 73.8 \text{ atm.}$$

* T_2 is estimated at 200 °F based upon the maximum coolant temperature (185 °F) and conservative analytical analyses which indicate that all available heat at the enriched-depleted pellet interface transferred axially through the depleted pellet and nickel reflector would be dissipated within these components.

2. Helium Expansion

$$P_2 = \frac{P_1 V_1 T_2}{V_2 T_1}$$

$$P_1 = 1 \text{ atm.}$$

$$V_1 = 0.301 \text{ in}^3$$

$$T_1 = 530 \text{ }^\circ\text{R}$$

$$T_2 = 660 \text{ }^\circ\text{R}$$

$$V_2 = 0.275 \text{ in}^3$$

$$P_2 = \frac{(1 \text{ atm})(0.301)(660)}{(0.275)(530)}$$

$$= 1.36 \text{ atm.}$$

3. Moisture

Assume: Fuel contains < 30 ppm moisture

Each mole of H_2O produces 1.5 moles gas

Total fuel wt. = 32 in. x 5.97 gm/in. = 190.7 gm

$$N_g = \frac{(1.5 \text{ moles})(190.7 \text{ gm})(30 \times 10^{-6} \text{ gm H}_2\text{O/mole})}{(18 \text{ gm H}_2\text{O/mole})}$$

$$= 4.8 \times 10^{-4} \text{ gram-mole}$$

$$P_{\text{H}_2\text{O}} = \frac{(4.8 \times 10^{-4})(82.06)(93 + 273)}{(0.275)(16.4)}$$

$$= 3.2 \text{ atm.}$$

4. Absorbed and Adsorbed GasesAssume 100% release @ 0.06 cm³ gas/gm fuel

$$N_g = \frac{(1 \text{ atm})(190.7 \text{ gm})(0.06 \text{ cm}^3/\text{gm})}{(82.06)(21 + 273)}$$

$$= 4.74 \times 10^{-4} \text{ gram-mole}$$

$$P_g = \frac{(4.74 \times 10^{-4})(82.06)(93 + 273)}{(0.275)(16.4)}$$

$$= 3.2 \text{ atm.}$$

C. NaK Annulus Pressure1. Normal Operation

	<u>Room Temp. (70 °F)</u>	<u>Oper. Temp.</u>
Cavity Volume	17.27 in ³	17.18 in ³
NaK Volume	9.52 in ³	10.11 in ³
Void Volume	7.75 in ³	7.07 in ³
Void Temp.	530 °R	660 °R
He Pressure	2 atm.	2.73 atm.

$$P_2 = P_1 \frac{V_1}{V_2} \cdot \frac{T_2}{T_1}$$

$$= 2 \text{ atm} \left(\frac{7.75 \text{ in}^3}{7.07 \text{ in}^3} \right) \left(\frac{660 \text{ °R}}{530 \text{ °R}} \right)$$

$$= 2.73 \text{ atm.}$$

2. Fuel Pin Failure

(fuel pin gases released to NaK annulus)

where:

$$P_1 = 2 \text{ atm.}$$

$$V_1 = 0.301 + 7.75 = 8.051 \text{ in.}^3$$

$$V_2 = 0.275 + 7.07 = 7.345 \text{ in.}^3$$

$$T_1 = 70 + 460 = 530 \text{ }^\circ\text{R}$$

$$T_2 = 200 + 460 = 660 \text{ }^\circ\text{R}$$

$$n_1 = \text{Initial moles of gas} = 8.051 \text{ in.}^3 \text{ (STP)}$$

$$n_2 = \text{Final moles of gas} = 27.392 \text{ in.}^3$$

$$\text{where } n_2 = 8.051 + 16.301 + m + a$$

$$\text{and } \frac{16.301 \text{ in.}^3}{73.8 \text{ atm.}} = \frac{m}{3.2 \text{ atm.}} = \frac{a}{3.2 \text{ atm.}}$$

$$n_2 = 8.051 + 16.301 + 0.7 + 0.7 = 25.8 \text{ in.}^3$$

$$\begin{aligned} P_2 &= P_1 \frac{V_1}{V_2} \frac{T_2}{T_1} \frac{n_2}{n_1} \\ &= 2 \text{ atm.} \cdot \frac{8.051}{7.345} \cdot \frac{660}{530} \cdot \frac{25.8}{8.051} \\ &= 8.8 \text{ atm.} \end{aligned}$$

D. Stress Arising From Internal Pressure (50,000 Mwd/MIM Capsule)1. Fuel Pin

$$\sigma_H = \frac{PD}{2t}$$

where:

$$P = (73.8 + 1.36 + 3.2 + 3.2) - 14.7 = 1200 \text{ psia}$$

$$D = \text{mean diam.} = 0.234 \text{ in.}$$

$$\sigma_H = \frac{1200 \text{ psi} \times 0.234}{2(0.016)}$$

$$= 8775 \text{ psi}$$

2. Outer Containment

$$\sigma_H = \frac{PD}{2t}$$

$$= \frac{(2.73 \times 14.7)(1.077)}{2(0.049)}$$

$$= 442 \text{ psi}$$

3. Outer Containment (if fuel pin fails)

$$\sigma_H = \frac{(8.8 \times 14.7)(1.077)}{2(0.049)}$$

$$= 1428 \text{ psi}$$

E. Thermal Stress

$$\sigma_H = \frac{E \alpha \Delta T}{2(1-\mu)}$$

1. Fuel Pin

$$\begin{aligned}\sigma_H &= \frac{(28 \times 10^6 \text{ psi})(10.2 \times 10^{-6} \text{ in/in-}\alpha\text{T})(88 \text{ }^\circ\text{F})}{2(1-0.3)} \\ &= 18,000 \text{ psi}\end{aligned}$$

2. Outer Containment

$$\begin{aligned}\sigma_H &= \frac{(28 \times 10^6)(9.9 \times 10^{-6})(83)}{2(1-0.3)} \\ &= 16,400 \text{ psi}\end{aligned}$$

F. Design Stress Limits ⁽⁷⁾ (See Figure A-8)1. Fuel PinN-414.1General primary membrane stress intensity (P_m) (I-220, P100)

$$P_m = \frac{P^R}{t} + \frac{P}{2}$$

$$P = 1271 \text{ psi}$$

$$R = 0.109 \text{ in.}$$

$$t = 0.016 \text{ in.}$$

$$\begin{aligned}S &= \frac{(1200 \text{ psi})(0.109 \text{ in.})}{(0.016 \text{ in.})} + \frac{(1200 \text{ psi})}{2} \\ &= 8175 \text{ psi} + 600 \text{ psi} \\ &= 8775 \text{ psi}\end{aligned}$$

$$\text{Design limit} = S_m \text{ (Table N-4:21)} = 14,500 \text{ psi @ } 900 \text{ }^\circ\text{F.}$$

N-414.2

Local membrane stress intensity (P_L)

$$P_L = P_m = 8775$$

$$\text{Design limit} = 1.5 S_m = 21,750 \text{ psi}$$

N-414.3

Primary membrane plus primary bending stress intensity

$$P_L + P_b$$

$$P + P_b = 8775 \text{ psi} + 0 \text{ psi} = 8775 \text{ psi}$$

$$\text{Design limit} = 21,750 \text{ psi}$$

N-414.4

Primary plus secondary stress intensity

$$P_L + Q = 8775 \text{ psi} + 0 = 8775 \text{ psi}$$

$$\text{Design limit} = 3S_m = 43,500 \text{ psi}$$

N-414.5

Peak stress intensity

$$P_L + P_b + Q + F$$

$$8775 \text{ psi} + 0 + 0 + 18,000 \text{ psi} = 26,775 \text{ psi}$$

$$\text{Design limit} = S_a = 43,500 \text{ psi}$$

N-415.1

Cycle operation (design limits)

$$a) S_a = 3 S_m = 3 (14500 \text{ psi}) = 43,500 \text{ psi}$$

$$\text{Maximum number of design cycles} = 3.5 \times 10^4$$

$$\text{Actual number of operating cycles} < 100$$

b) Full range of pressure fluctuation = P

$$P < \text{Design pressure} \times \frac{1}{3} \times \frac{S_a}{S_m}$$

where:

$$\text{Design pressure} = 1200 \text{ psi}$$

$$S_a = 110,000 \text{ psi (Fig N-415-B) @ 1000 cycles}$$

$$S_m = 14,500 \text{ psi (Table N-421) @ 900 }^\circ\text{F}$$

$$P < 1200 \text{ psi} \times \frac{1}{3} \times \frac{110,000 \text{ psi}}{14,500 \text{ psi}}$$

$$P < 3029 \text{ psi}$$

actual number of operating cycles < 100

actual P = 1200 psi

c) ΔT at any two adjacent points during operation shall be

$$S_a / (2 E \alpha)$$

where

$$S_a = 240,000 \text{ psi @ 100 cycles}$$

$$\rightarrow E = 28 \times 10^6 \text{ psi}$$

$$\rightarrow \alpha = 10.7 \times 10^{-6} \text{ in/in } - ^\circ\text{F @ } 8750 ^\circ\text{F}$$

$$\begin{aligned} S_a / (2 E \alpha) &= 240,000 \text{ psi} / (2 \times 28 \times 10^6 \text{ psi} \times 10.7 \times 10^{-6} \text{ in/in } \cdot ^\circ\text{F}) \\ &= 400 ^\circ\text{F} \end{aligned}$$

$$\Delta T @ \text{ peak position} = 88 ^\circ\text{F} < 400 ^\circ\text{F}$$

d) Not applicable:

Section "C" indicates that the required design limit has been met.

e) Not applicable

Materials of construction for fuel pin are of same material
(tube and end caps)

f) Not applicable

All mechanical load is applied by internal pressure.

N-417-3

Thermal stress ratchet

where:

$Y' = \text{max. allowable range of thermal stress, divided by}$
yield strength

$X = \text{max hoop stress due to pressure divided by yield strength.}$

$$X = 8775 \text{ psi} / 15,600 \text{ psi} = 0.562$$

$$Y' = 4(1 - 0.562) = 1.76$$

$$\sigma_{th} = (1.76)(16,100 \text{ psi}) = 28,100 \text{ psi}$$

2. Outer Container:

N-414.1

General primary membrane stress intensity (P_m)

$$P_m = 1428 \text{ psi}$$

$$\text{Design limit} = S_m = 19,800 \text{ psi}$$

N-414.2

Local membrane stress intensity (P_L)

assume 50% weld penetration

$$P_L = 2 P_m = 2856 \text{ psi}$$

$$\text{Design limit} = 1.5 S_m = 29,700 \text{ psi}$$

N-414.3

Local membrane plus primary bending stress intensity

$$P_L + P_b = 2856 \text{ psi} + 0_{\text{psi}} = 2856 \text{ psi}$$

$$\text{Design Limit} = 1.5 (S_m) = 29,700 \text{ psi}$$

N-414.4

Local plus secondary stress intensity

$$P_m + Q = 2856 \text{ psi} + 0 = 2856 \text{ psi}$$

$$\text{Design limit} = 3 S_m = 59,400 \text{ psi}$$

N-414.5

Peak stress intensity

$$P_L + P_b + Q + F = (2856 + 0 + 0 + 16,400) \text{ psi} = 19,256 \text{ psi}$$

$$\text{Design Limit} = S_a = 59,400 \text{ psi}$$

N-415.1

Cyclic operation (design limits)

$$a) S_a = 3(19,800 \text{ psi}) = 59,400 \text{ psi}$$

$$\text{Max. number of design cycles} = 10,000$$

$$\text{Actual number of operating cycles} < 100.$$

- b) Full range of pressure fluctuation (\underline{p})

$$P < \text{design pressure} \times \frac{1}{3} \times \frac{S_a}{S_m}$$

where:

$$P = (8.8 \text{ atm})(14.7 \text{ psi/atm}) = 129 \text{ psi}$$

$$S_a = 110,000 \text{ psi (Fig N-415 B) @ 1000 cycles}$$

$$S_m = 19,888 \text{ psi}$$

$$P < 129 \text{ psi} \times \frac{1}{3} \times \frac{110,000}{19,800}$$

$$P < 239 \text{ psi}$$

actual number of operating cycles < 129 psi

- c) ΔT at any two adjacent points during operation shall be

$$< S_a / (2 E \alpha)$$

where:

$$S_a = 240,000 \text{ psi @ 100 cycles}$$

$$E = 28 \times 10^6 \text{ psi}$$

$$\alpha = 9.9 \times 10^{-6} \text{ in/in. } ^\circ\text{F}$$

$$S_a / (2 E \alpha) = 433 \text{ } ^\circ\text{F}$$

$$\Delta T @ \text{ peak position} = 83 \text{ } ^\circ\text{F} < 433 \text{ } ^\circ\text{F}$$

- d) Not applicable

- e) Not applicable

- f) Not applicable

N-417.3

Thermal stress ratchet

where:

Y' = Maximum allowable range of thermal stress divided by yield strength

X = maximum hoop stress due to pressure divided by yield strength

$X = 2856 \text{ psi} / 23,500 \text{ psi} = 0.121$

$Y' = 1 / 0.121 = 8.3$

$\sigma_{th} = (8.3)(23,500 \text{ psi}) = 194,000 \text{ psi}$

G. Summary of Stress Conditions

ASME P.V. CODE, VOL 3 1965 Edition Paragraph No.	Stress Component	Fuel Pin		Outer Containment*	
		Design Condition	Design Limit	Design Condition	Design Limit
	Internal Pressure	1,200 psi	-	40 psi	-
	Thermal Stress	18,000 psi	-	16,400 psi	-
N-414.1	Gen. Primary Stress Intensity	8,775 psi	14,500 psi	1,428 psi	19,800 psi
N-414.2	Local Membrane Stress Intensity	8,775 psi	21,750 psi	2,856 psi	29,700 psi
N-414.3	Primary Membrane + Primary Bending Stress Intensity	8,775 psi	21,750 psi	2,856 psi	29,700 psi
N-414.4	Primary + Secondary Stress Inten.	26,775 psi	43,500 psi	2,856 psi	59,400 psi
N-414.5	Peak Stress Intensity	26,775 psi	43,500 psi @ 46,000 cycles	19,256 psi	59,400 psi @ 10,000 cycles
N-415.1	Cyclic Operation (no. of cycles)	< 100 cyc.	-	< 100 cycles	-
	a. S_a	-	43,500 psi @ 46,000 cycles	-	59,400 psi @ 10,000 cycles
	b. Maximum Pressure Range	1200 psi	3029 psi @ 1000 cycles	129 psi	239 psi @ 10,000 cycles
	c. Max. ΔT at two adjacent points	88 °F	400 °F	83 °F	432 °F
	d. Not applicable	-	-	-	-
	e. Not applicable	-	-	-	-
	f. Not applicable	-	-	-	-
N-417.3	Thermal Ratchet Mechanism				
	Pressure Stress	8775 psi	8775 psi	2856 psi	2856 psi
	Thermal Stress	18,000 psi	28,100 psi	16,400 psi	19,400 psi

*Outer containment design conditions assume fuel pin failure at the end of 50,000 MWd/MTM burnup and 50% penetration on closure welds. Though neither of these conditions should occur, the assumptions are made to assure conservatism in the stress analysis.

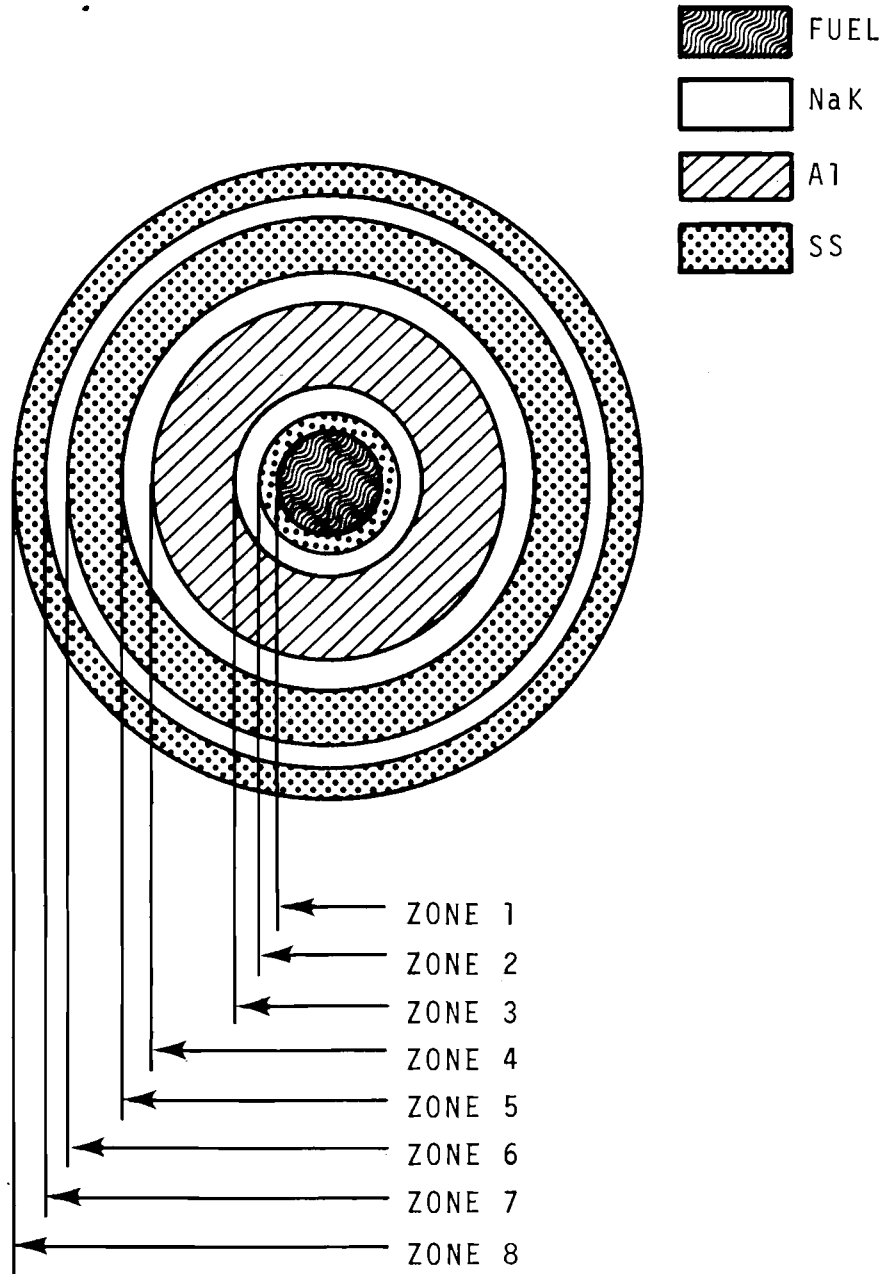


FIGURE A-1. Zone Identification
PNL 59-1 through PNL 59-12

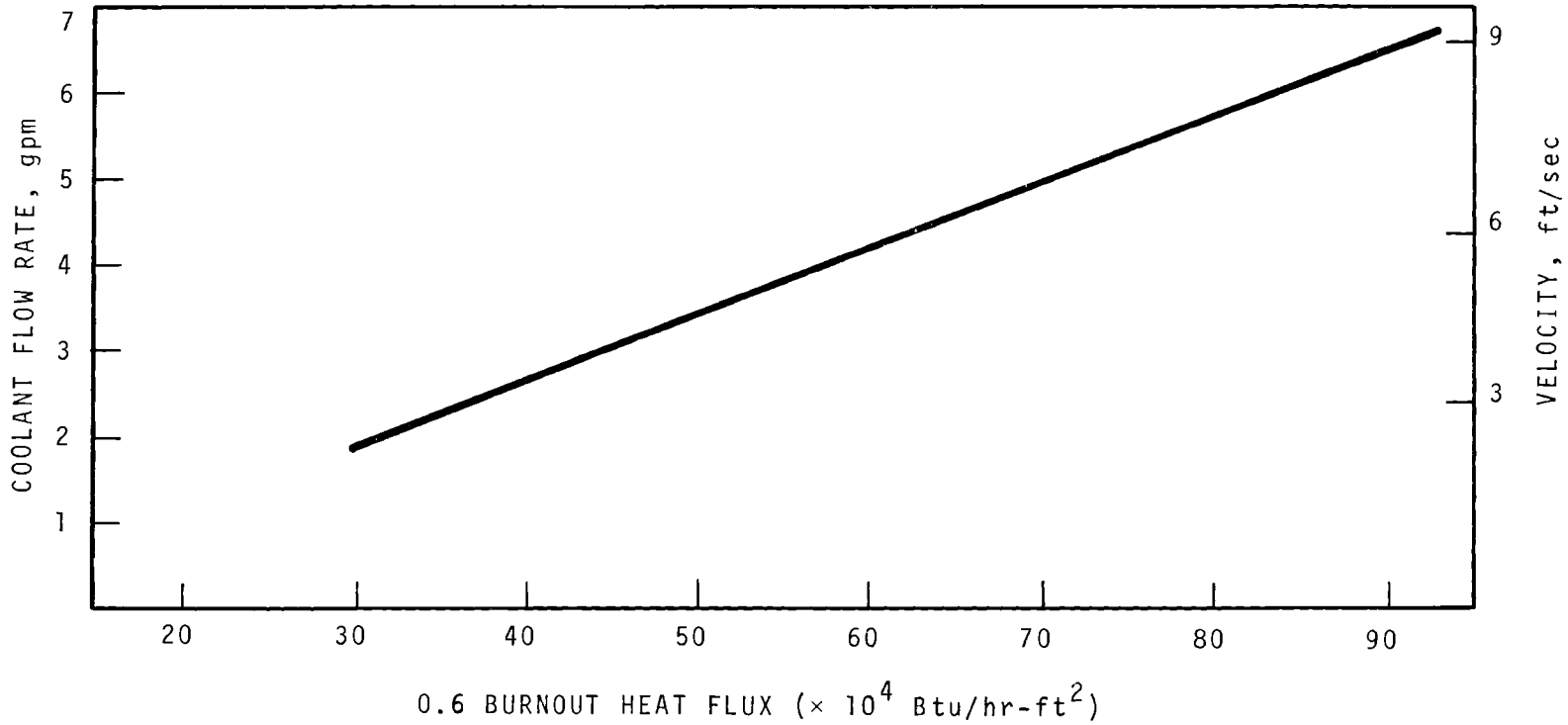


FIGURE A-2. Coolant Flow Rate Versus 0.6 Burnout Heat Flux
Capsules PNL 59-1 through PNL 59-12

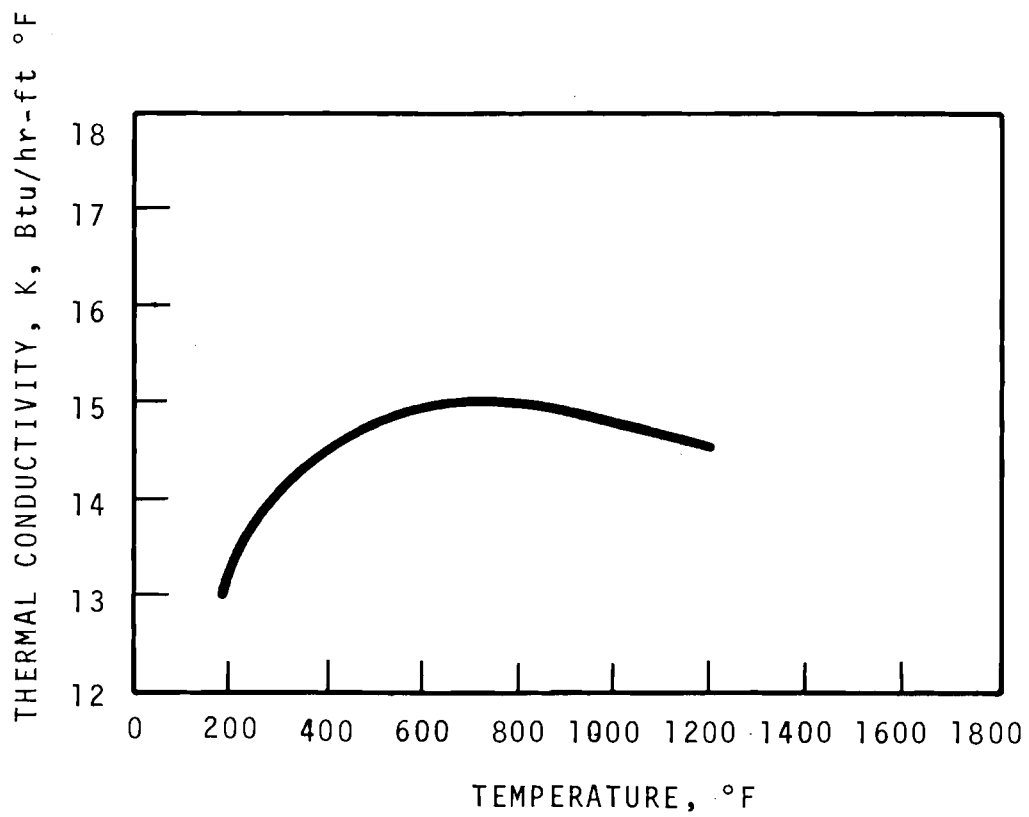


FIGURE A-3. Thermal Conductivity of NaK-78
(From Liquid Metals Handbook -
NaK Supplement, p. 40)

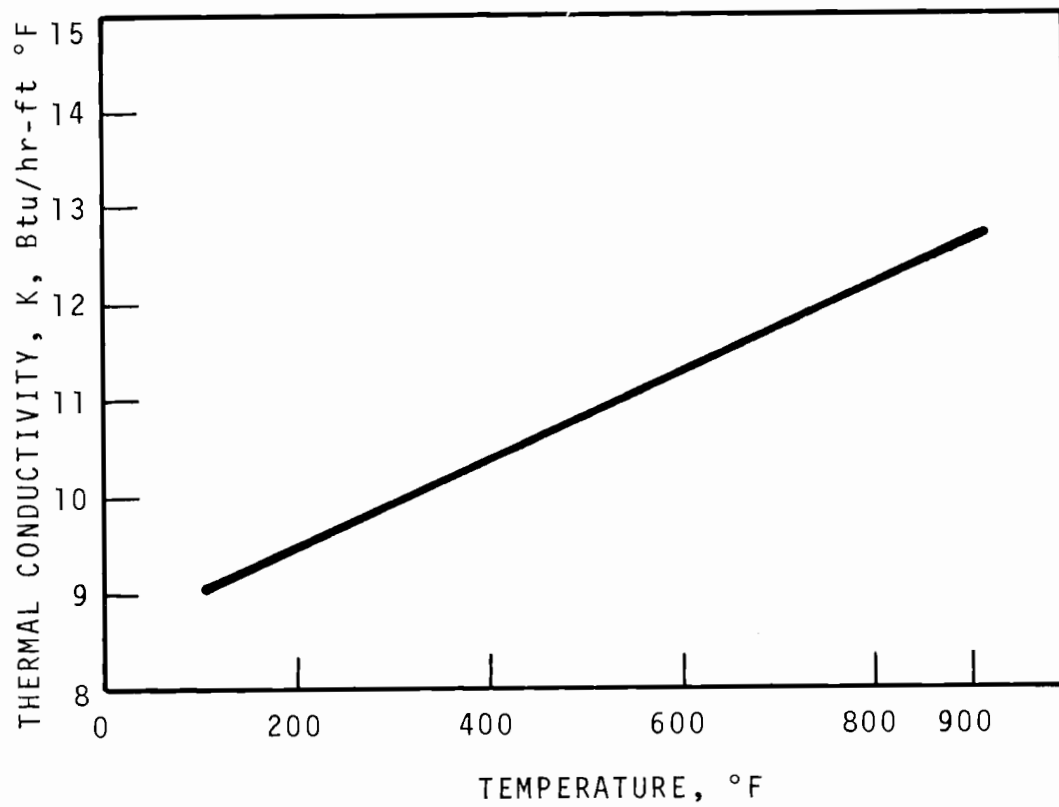


FIGURE A-4. Thermal Conductivity of 304 SS
(From Metals Handbook, 8th Ed.)

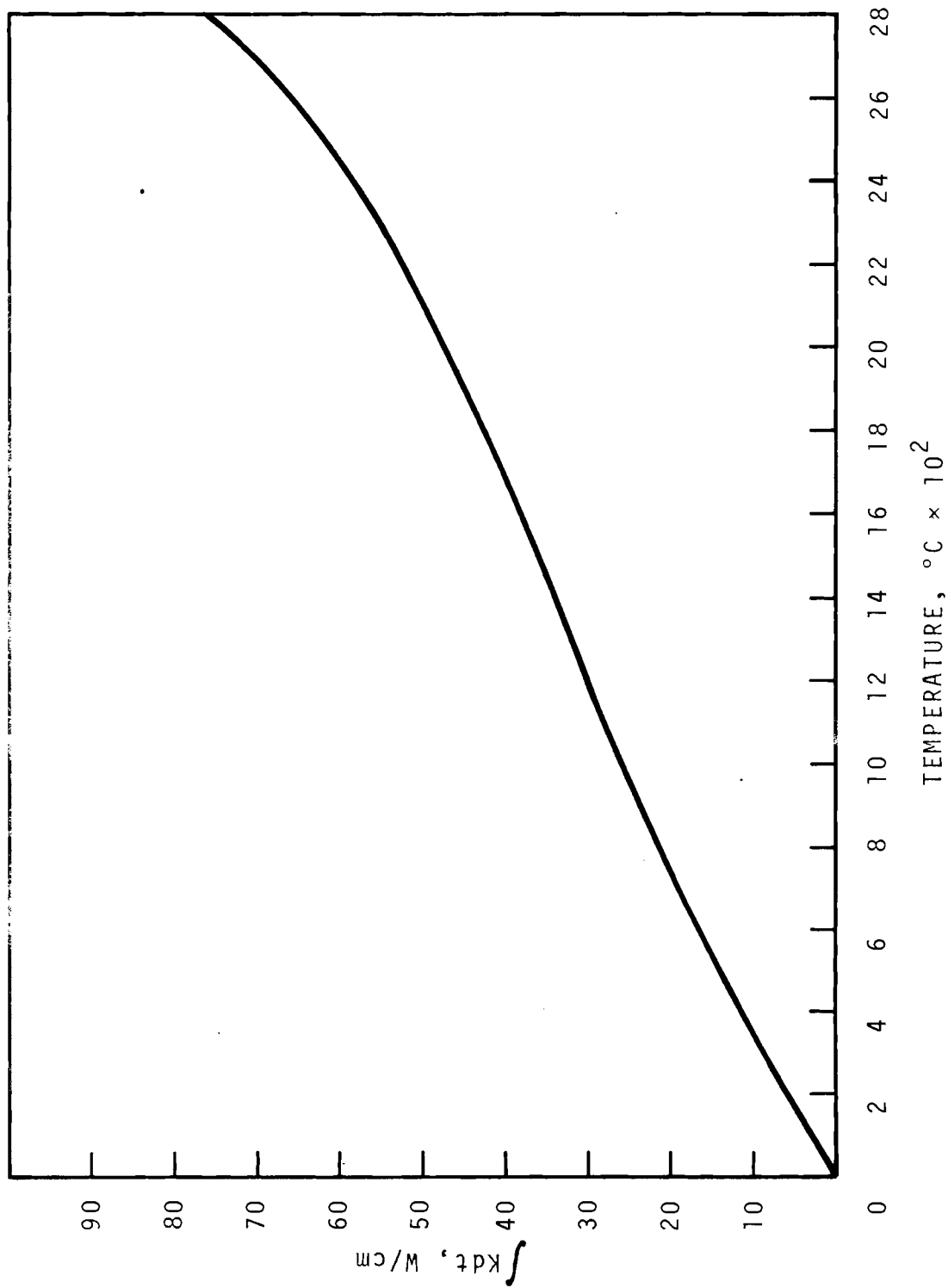


FIGURE A-5. $\int K dt$ for Mixed Oxide Pellets

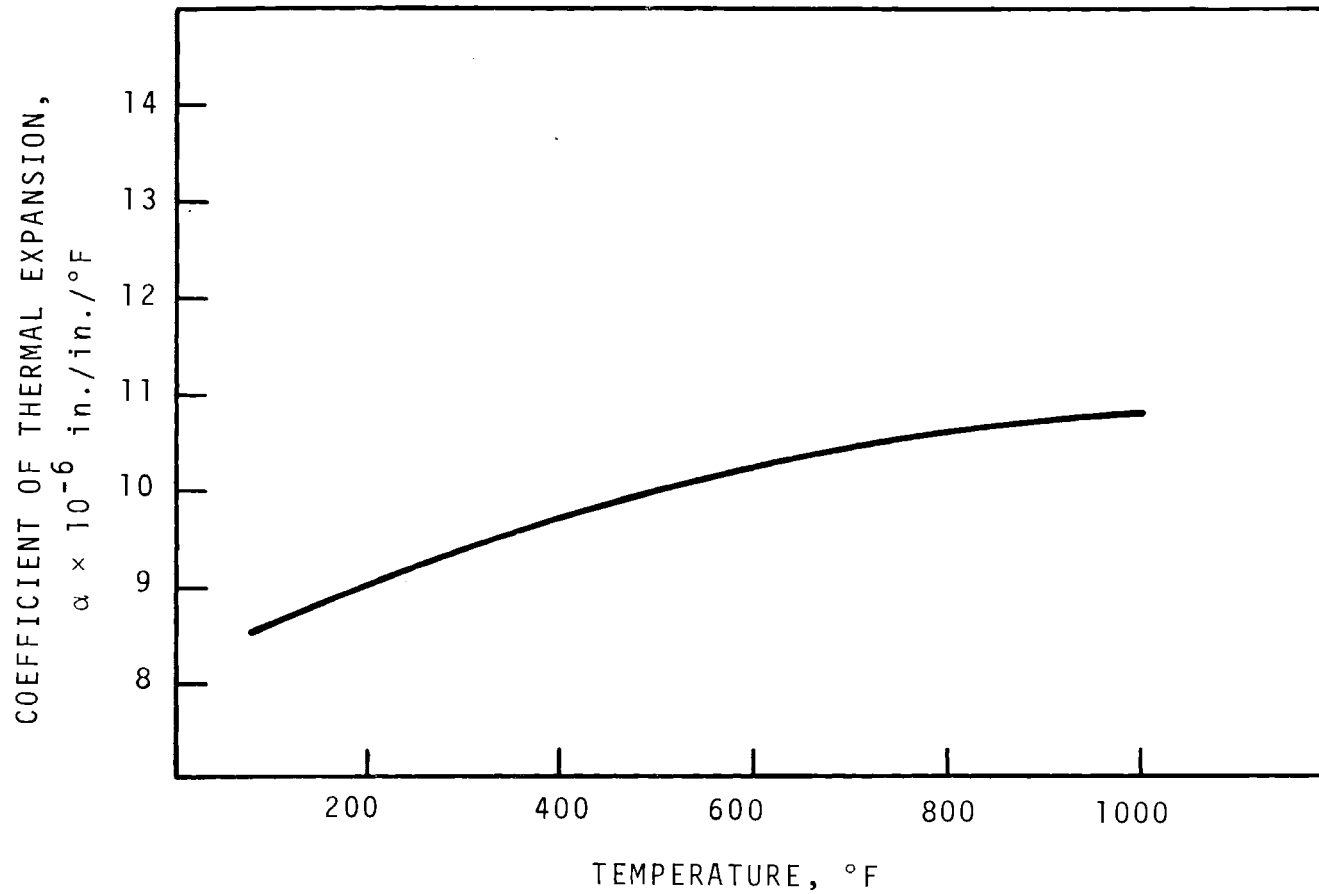


FIGURE A-6. Coefficient of Thermal Expansion for 304 SS
(From U.S. Dept. of Commerce, Tentative
Structural Design for Pressure Vessels - 1958)

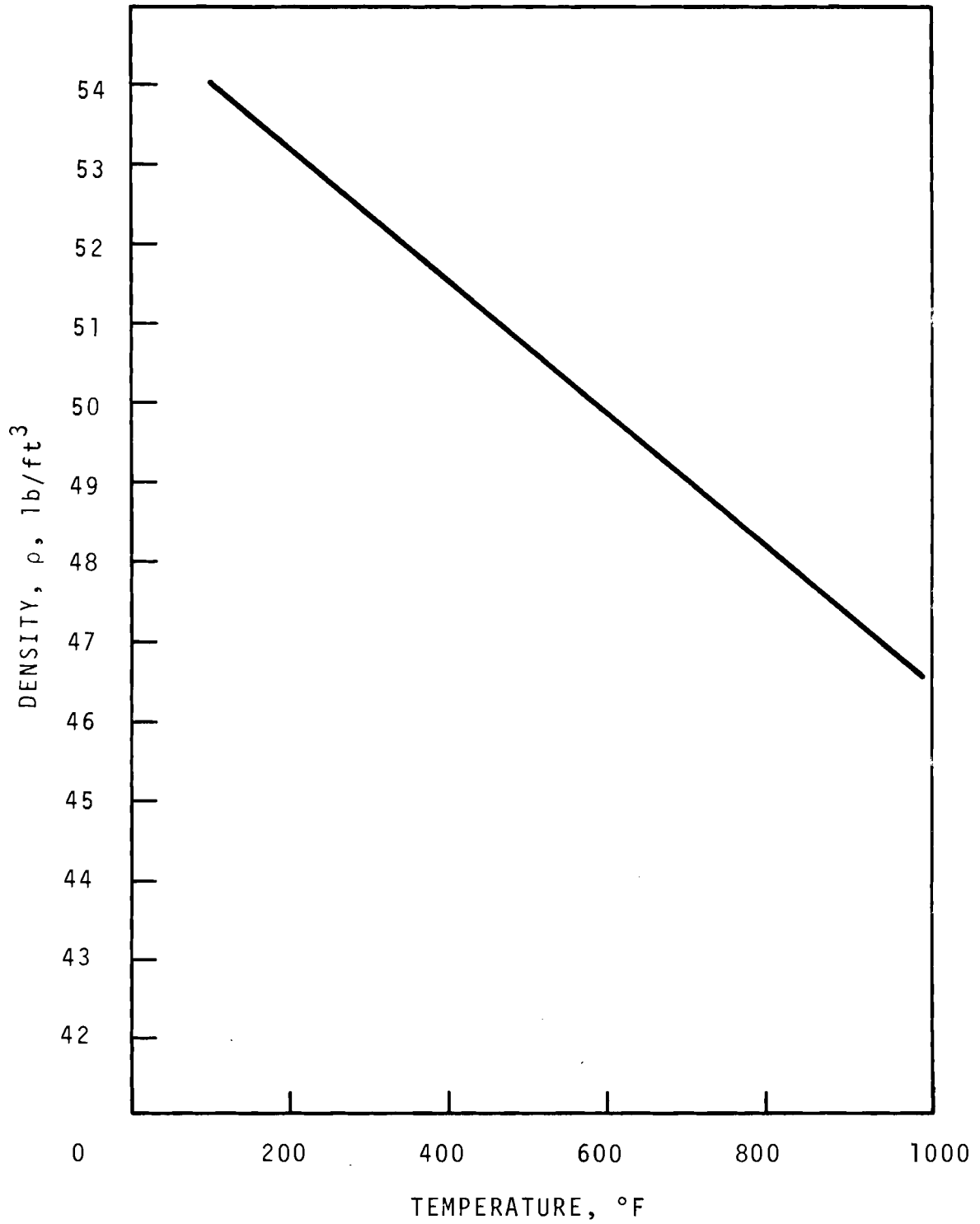


FIGURE A-7. Density of NaK-78 (from Liquid Metals Handbook, NaK Supplement)

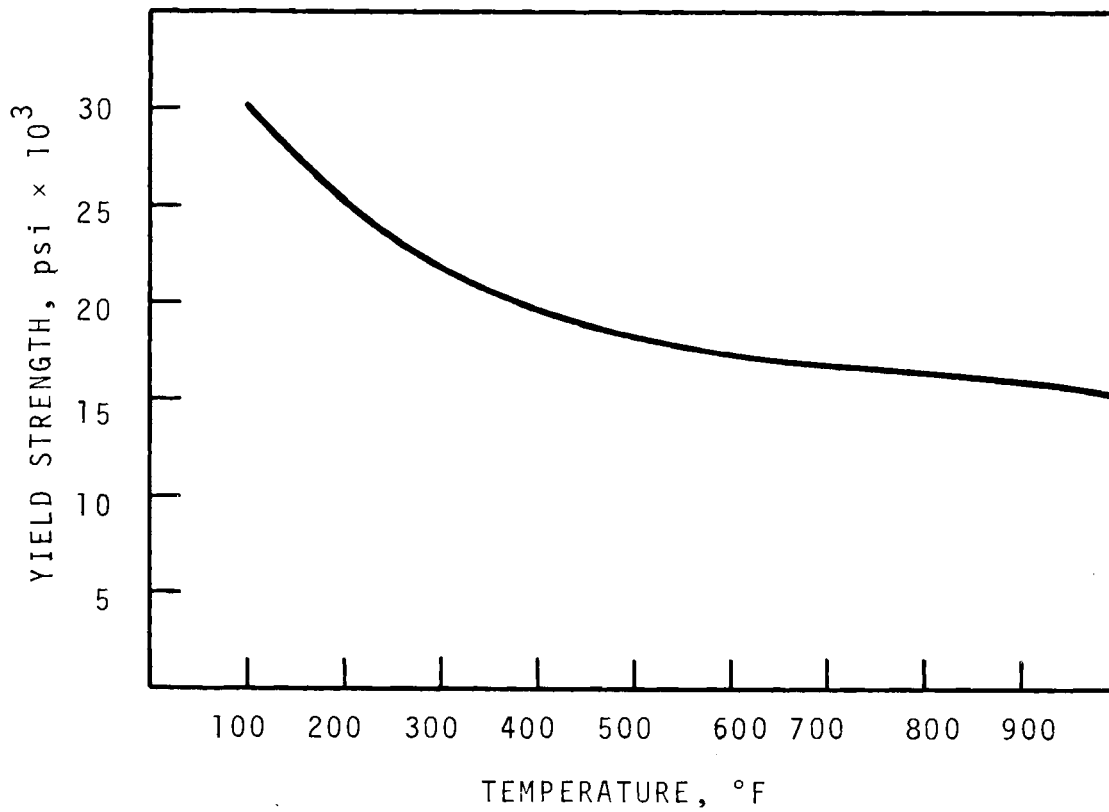


FIGURE A-8. Yield Strength for Annealed 304 SS Tubing
(ASME Boiler and Pressure Vessel Code)

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