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TME 834

WANL Fuel Material Irradiation Program

Capsule Series T-T

Phase II

Safeguards Report

D. C. Jacobs

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Prepared by:

D. C. Jacobs
D. C. Jacobs

Approved by:

M. A. Vogel
M. A. Vogel, Supr.

A. Boltax
A. Boltax, Mgr.
Fuel Development
Materials Department

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A. Boltax 6/24/64

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I. Introduction

The purpose of the program outlined herein is to ascertain the radiation behavior of NERVA fuel material. This phase of the program will involve the irradiation of six capsule assemblies. These capsule assemblies are quite similar to those which have been previously irradiated at the GETR.

The prime test element will be fueled graphite containing pyro-carbon coated UC_2 . Each sample will be in form of cylindrical pellets with an 0.577 inch diameter and 0.995 inch length. There will be four such pellets in each capsule assembly.

The fuel pellets are to have one of the following pre-irradiation treatments:

- (a) No treatment
- (b) Held at $2400^{\circ}C$ for 0.5 hr. and stored in air.
- (c) Held at $2400^{\circ}C$ for 0.5 hr. and stored in an inert atmosphere.

Any given capsule assembly will contain pellets which have received the same pre-treatment.

The fuel pellets are to receive the required burn-up at specific temperatures. One capsule (T-T8) is to be irradiated two separate times. The pertinent parameters are outlined in Table I.

This safeguards analysis has been made in as general a fashion as possible. This was done so that the data would be applicable over

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Table I - Irradiation Parameters

<u>Capsule</u>	<u>Pre-treatment</u>	<u>Max. Temp. (°C)</u>	<u>Max. Burnup (fiss/cm³)</u>	<u>Probable Flux** (n/cm² sec)</u>	<u>Irrad.Time (min)</u>
T-T7	None	2700	1.5×10^{17}	6.2×10^{13}	105.5
T-T8	None	2700	$1.5 \times 10^{17*}$	6.2×10^{13}	105.5*
T-T9	None	2200	1.5×10^{17}	4.2×10^{13}	155.7
T-T10	Stored inert atmos.	2500	1.5×10^{17}	5.4×10^{13}	121.1
T-T11	Air Stored	2700	1.5×10^{17}	6.2×10^{13}	105.5
T-T12	Air Stored	2200	1.5×10^{17}	4.2×10^{13}	155.7

* Burnup to be accomplished in two separate insertions

** Unperturbed flux

a wide range of operating conditions thereby allowing a WANL representative considerable latitude in changing the irradiation parameters if he so desires.

II The Capsule Assembly

The capsule assembly is shown in WANL drawing 576F385. Except for the thermocouples, all metallic parts are of type 304 stainless steel.

Two containers are provided. The inner can, containing the test specimens will be under vacuum. The inner surface of the inner can will be coated with Spray Graph so as to increase the emissivity of the surface. An 0.050 inch annulus is provided between the inner and outer cans. A stainless steel sheathed, iron/constantan thermocouple is provided to monitor annular water temperatures. Co-Al flux monitor wires, extending the length of the inner can, will be attached to the outer surface of the inner can.

Each capsule will contain four fuel pellets. The fuel pellets are held within a graphite sleeve. Each pellet will have associated with it a tantalum sheathed, BeO insulated, W-5% Re/W-26% Re thermocouple. The hot junction of each thermocouple will be located at the surface of the fuel pellet. So as to facilitate brazing a transition from the tantalum sheath to stainless steel is made at the upper end of the thermocouple.

[REDACTED]

Each thermocouple enters the inner can through its individual hole in the inner can lid. These holes will be sealed (helium-leak tight) by brazing.

The thermocouples are taken through the outer can by means of holes in the outer can lid. The holes will be sealed (water tight) by brazing. Once through the outer can lid the thermocouples are connected to 40 feet of lead wire. The connections are protected from water and damage by a potting nipple which is welded to the top of the outer can lid. The lead wires pass out of the trail cable facility through a flexible metal hose which terminates at an Anphenol multi-conductor connector.

The coolant water enters the outer can through a hole in the outer can lid. The water is carried from the GETR supply through 44 feet of flexible metal hose (0.75" nominal I.D.). A 4 foot section of the hose is permanently attached to each capsule. The remaining 40 feet will be reused for each irradiation. The out-of-pile water inlet terminates at a quick disconnect coupling which will be connected directly to the GETR water supply.

III Instrumentation and Hardware

The instrumentation and hardware can be divided into four systems, (a) the coolant delivery system, (b) the coolant temperature monitoring system, (c) the timing system, and (d) the thermocouple

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recorder system. Each system is described in detail below.

A. The Coolant Delivery System

The coolant delivery system consists of 44 feet of braided, flexible, metal hose. The inside diameter of the hose is 0.75 inch and the outside diameter is 1.07 inches. The hose is rated as having a 500 psi working pressure. The hose will be in two parts, (a) a 40 foot reuseable section, and (b) a 4 foot section which will be permanently connected to each capsule.

The out-of-pile section of the flexible metal hose terminates with a quick disconnect socket. The hose will be connected directly to the GETR water supply. GETR is to supply the appropriate flow and pressure monitoring devices.

B. The Coolant Temperature Monitoring System

The purpose of the coolant temperature monitoring system is to alarm a boiling condition within the water annulus of the capsule assembly. The principal instrument in the system is a signaling controller, (Thermoelectric #80025). The input signal is received from an iron (+)/constantan (-) thermocouple located within the water annulus of the capsule assembly.

Both visual and audible alarms are provided. The visual alarm is an integral part of the signalling controller. For convenience an audible alarm by-pass is provided. A by-pass indicator is also provided so as to alert an operator if the audible alarm has been

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by-passed.

C. The Timing System

The timing system is provided to allow the operator to accurately record elapsed time during an insertion. The principal instrument in the system is a running time meter with a zero reset. The full range of the meter is 10^4 minutes and the unit count is 0.1 minute. The system also includes a switch and an indicator light.

D. The Thermocouple-Recorder System

The thermocouple-recorder system is shown in Figure 1. The W-5% Re/W-26% Re thermocouples are numbered from bottom to top i.e., the thermocouple associated with the bottom pellet is designated #1, etc. The iron/constantan thermocouple in the coolant annulus is designated by W.

The thermocouple-recorder system is divided into 4 segments (1) the trail cable segment, (2) the extension cable segment, (3) the instrument cabinet segment, and (4) the recorder segment. A description of each segment follows.

1. The Trail-Cable Segment

In the trail-cable segment of the system, all thermocouple leads are brought out of the trail-cable facility through a stainless steel flexible hose. The leads terminate at a socket type Anphenol connector (3106 A-24-28S).

2. The Extension Cable Segment

The extension cable segment consists of 5 pairs of

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Thermocouple-Recorder System

lead wire bundled in polyethylene tubing. The cable will link the trail-cable segment to the instrument panel segment. The leads at one end of the extension cable are connected to a pin type Anphenol connector (3101 A-24-28P) which mates with connector in the trail-cable segment. The leads at the other end of the extension cable are connected to a socket type Anphenol connector (3106 A-24-28S) which mates with a panel mounted connector.

3. The Instrument Panel Segment

All 5 pairs of lead wire enter the instrument panel through a panel mounted, pin type, Anphenol connector (3102 A-24-28P). The iron/constantan lead wires are taken to the signaling controller and the W-5% Re/W-26% Re wires are connected to another pin type, panel mounted Anphenol connector (3102 A-24-28P) which serves to take the leads out of the instrument cabinet.

4. The Recorder Segment

In the recorder segment the four pairs of W-5% Re/W-26% Re lead wires, bundled in polyethylene tubing are taken from the instrument cabinet by means of a socket type Anphenol connector which mates with the panel mounted connector. The leads then extend to the terminal board of the multi-point recorder.

Since the multi-point recorder will print out 24 points and since only four thermocouples are in use, the terminal board must be modified in such a way that the input signal from a given thermocouple

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is recorded as more than one point. Table 2 outlines the required thermocouple-recorder point relationship. Included in the table is the letter designation of each thermocouple lead in the Anphenol connectors.

IV Neutron Flux Distribution

A. Radial Distribution

The radial, thermal neutron flux distribution within the capsule assembly is shown in Figure 2. The distribution was calculated using the equation:

$$\phi(r)/\phi_{\infty} = \prod_{n=1}^6 \exp[\Sigma_n (r-r_o)_n]$$

where:

r_n = radial position within the n^{th} region

$\phi(r)$ = perturbed neutron flux

ϕ_{∞} = unperturbed neutron flux

Σ_n = macroscopic capture cross-section of the n^{th} region

r_{on} = outer radius of the n^{th} region

The data used in the computation are given in Table 3.

The mean perturbed flux within the fuel was calculated using the equation:

$$\bar{\phi}_f/\phi_{\infty} = 0.952 \int_0^{r_o} \exp[\Sigma(r-r_o)] dr / \int_0^{r_o} dr,$$

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Table 2 - Thermocouple-recorder Point Relationship

<u>Thermo-</u> <u>couple</u>	<u>Anphenol Letter</u>		<u>Recorder Points</u>
	<u>+ Lead</u>	<u>- Lead</u>	
1	A	B	1, 5, 9, 13, 17, 21
2	G	H	2, 6, 10, 14, 18, 22
3	K	L	3, 7, 11, 15, 19, 23
4	T	U	4, 8, 12, 16, 20, 24

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Table 3 - Data for Computation of Neutron Flux Distribution

<u>Region</u>	<u>Material</u>	<u>a (cm^{-1})</u>	<u>r_o (cm)</u>	<u>r_i (cm)</u>
1	Stainless Steel	0.308	2.74	2.67
2	Water	0.022	2.67	2.54
3	Stainless Steel	0.308	2.54	2.46
4	Radiation Gap	0.000	2.46	2.34
5	Graphite	0.0003	2.34	0.73
6	Fuel	0.593	0.73	0.00

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Figure 2

Radial Thermal Neutron Flux Distribution
in WAND T-T Series Capsule

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~~GROUP 1~~

where,
$$\prod_{n=1}^5 \exp[\sum_n (r-r_o)_n] = 0.952.$$

Therefore,

$$\begin{aligned}\bar{\phi}_f/\phi_{\infty} &= 0.952 [1 - \exp(-\sum r_o)]/\sum r_o \\ \bar{\phi}_f/\phi_{\infty} &= 0.770\end{aligned}$$

B. Axial Distribution

The cycle average, axial flux distribution within the trail cable facility is shown in Figure 3. The data for the plot was obtained from GETR*. The normalizing factor used in the calculation was 0.75×10^{14} .

As seen from Figure 3 the axial flux distribution can be approximately described by the equation

$$\phi_{\infty}(x) = 1.1 \times 10^{14} \cos(0.077x),$$

where x is measured in inches. $x = 0$ was taken at the flux peak located 14 inches from the bottom of the core. The above equation will be used in the thermal analysis section of this document.

V Thermal Analysis

A thermal analysis of the system has been made; the results are summarized in Figure 4. (The calculations appear in Appendix I).

* J. O. Arterburn, and B. Bastian, "GETR Neutron Fluxes", (Mar. 1, 1963).

Figure 4

It was shown that the temperature distributions within those regions internal to the radiation gap are essentially independent of the coolant temperature. Consequently, the thermal analysis for these regions was not based on any specific flux distribution.

However, in those regions affected by the coolant temperature, the thermal analysis was based on the cycle average flux distribution.

It is seen from Figure 4 that if the first fuel pellet is placed at the cycle average peak flux ($1.1 \times 10^{14} \text{ n/cm}^2 \text{ sec}$) no boiling occurs within the water annulus at flow rates $\geq 20 \text{ gal/min}$. The center-line temperature of the fuel pellet at this position will be 6800°F (3763°C).

VI Hydraulic Analysis

It was shown that a coolant flow rate of 20 gpm is sufficient to prevent boiling within the water annulus of the capsule assembly. It will now be shown that the coolant system to be used is capable of delivering 20 gpm.

The pressure drop in each segment of the system has been calculated, (see Appendix II). The results of the calculations are summarized in Table 4.

The delivery pressure is assumed to be 135 psi and the discharge pressure is assumed to be 13 psi, (the capsule is taken to be beneath 30 feet of water). Therefore, the maximum available pressure is $135 - 13 = 122 \text{ psi}$.

[REDACTED]

Table 4 - Pressure Drops in WANL Coolant System
For Flow Rate of 20 gpm

<u>Segment of System</u>	<u>Pressure Drop (psi)</u>
Flexible metal hose	70.4
Expansion into capsule	1.1
Contraction into coolant annulus	0.5
Flow through coolant annulus	1.4
Expansion into trail cable facility	1.0
Miscellaneous fittings	5.0
Total	79.4

[REDACTED]

Therefore, the available operating pressure is: $122 - 79.4 = 42.6$ psi indicating that a flow rate of 20 gpm can indeed be achieved.

VII Burn-out Analysis

By applying the equation of Mirshak et.al.* it can be shown that the heat flux at burnout for the T-T capsule system under 30 feet of water is:

$$q_{B.O.}^{\dagger} = 6.51 \times 10^5 (1 + 0.022 f)(1 + 0.00914 T_s) \quad (1)$$

where:

$$q_{B.O.}^{\dagger} = \text{heat flux at burnout (BTU/hr.ft}^2\text{)}$$

$$f = \text{fluid flow rate (gal/min)}$$

$$T_s = \text{subcooling (C}^\circ\text{)}$$

Equation (1) is plotted in Figure 5.

The heat flux as a function of neutron flux is given in (2).

$$q^{\dagger}(x) = q(x)/2\pi r_c = 2.08 \times 10^{-9} \phi_{\infty}(x)/2\pi r_c \quad (2)$$

where:

$$r_c = \text{radius of the inner can. Taking } r_c = 0.0833 \text{ ft. it is seen that } q^{\dagger}(x) = 3.98 \times 10^{-9} \phi_{\infty}(x) \quad (3)$$

Equation (3) is plotted in Figure 6. Note, that at the cycle average peak flux (1.1×10^{14} n/cm² sec) no burnout would occur even if a no-flow condition would arise.

* S. Mirshak, W. S. Durant, and R. H. Towell, DP-355

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Figure 5

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Figure 6

VIII Stress Analysis

A stress analysis has been made (see Appendix III). The results are shown in Figure 7.

Two components of stress were considered, (a) thermal stress, and (b) stresses resulting from hydrostatic pressure. In the latter case it was assumed that the capsule was beneath 30 feet of water and that the operational pressure of the system is 47.7 psi (see hydraulic analysis).

It is seen from Figure 7 that the limiting stress in the inner can is the axial tensile stress acting on the outer surface. Note that this stress equals the minimum tensile yield stress at $\phi_{\infty} = 8.6 \times 10^{13} \text{ n/cm}^2 \text{ sec}$.

IX Hazards Analysis

There are five possible hazardous situations associated with the irradiation of the WANL capsule assemblies. It will be shown that these situations are adequately provided for and thus do not represent a hazard to the GETR.

A. Loss of Electrical Power

If for any reason there were to be a loss of power to the instruments, the "systems on" indicator lamp would go out. If this should occur, the capsule assembly would be removed from the flux zone and kept there until normal power is restored.

Figure 7

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B. Insufficient Coolant Flow

If for some reason there were to be insufficient coolant flow, an operator would be alerted to the fact by the flow meter indication. If this went unnoticed and the situation persisted, the approach to boiling temperature in the coolant annulus would activate the high temperature alarms. The capsule assembly would then be removed from flux zone and kept there until sufficient coolant was again available.

C. Loss of Water from the In-channel Coolant Lead

If water were lost from the in-channel coolant lead due to a hose rupture or due to a disconnection, the flow meter would give no indication. However, the annular water temperature would rapidly approach that of the boiling thereby activating the high temperature alarms. The capsule assembly would then be removed from the flux zone and, if possible, the damage repaired.

D. Leak in the Inner Can

There would be no way of detecting a leak in the inner can during an insertion. However, such a leak would be highly improbable since the inner can will be thoroughly leak checked prior to shipment to GETR. Since the inner can is protected by the outer can, it is improbable that a leak could develop as a result of damage during shipment or handling.

E. A Damaged Coolant Temperature Monitoring Thermocouple

The no-signal input condition that would arise from an

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open circuit in the thermocouple located in the water annulus would activate the high temperature alarms. It is most likely that damage to the thermocouple or its leads or connectors would have occurred during shipment or handling. Therefore, if such damage did occur, the alarms would be activated before the capsule assembly was inserted. If the thermocouples were inoperable the capsule could still be irradiated as an un-instrumented assembly.

X Summary

The safeguards analysis has been made in as general a fashion as possible. A wide range of irradiation conditions have been considered.

The most limiting factor was found to be the stresses developed within the inner stainless steel can. It was shown that the lower limit of the range of tensile yield stress for 304 stainless steel is reached at an unperturbed thermal neutron flux of $8.6 \times 10^{13} \text{n/cm}^2 \text{sec}$, (see Figure 7).

At an unperturbed thermal neutron flux of $8.6 \times 10^{13} \text{n/cm}^2 \text{sec}$ the fuel centerline temperature will be 6000°F ($3,250^\circ \text{C}$), (see Figure 4). Assuming a cycle average flux distribution, no film or annular boiling would occur at a peak flux of $8.6 \times 10^{13} \text{n/cm}^2 \text{sec}$ if the water flow rate $\geq 15 \text{ gal/min}$, (see Figure 4). It was shown that the WANL coolant system can deliver 15 gal/min .

The heat flux at burnout for a coolant flow rate of 15 gal/min

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is $12.8 \times 10^5 \text{ BTU/hr ft}^2$, (see Figure 5). The heat flux at $8.6 \times 10^{13} \text{ n/cm}^2 \text{ sec}$ is $3.5 \times 10^5 \text{ BTU/hr ft}^2$, (see Figure 6). Therefore, there is no danger of burnout at the maximum allowable conditions.

All possible hazardous situations related to the insertion of the capsule assemblies have been considered. It has been shown that all incidents are provided for by the WANL-GETR instrumentation system.

Consequently, it may be concluded from the foregoing, that the WANL capsule assemblies can be exposed to unperturbed, thermal neutron fluxes up to $8.6 \times 10^{13} \text{ n/cm}^2 \text{ sec}$ with no hazard to the GETR.

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Appendix I - Calculations for the Thermal Analysis

A. Fission Heating Rate Density

The average fission heating rate density at any axial position is described by equation (1).

$$Q(x) = 3.02 \times 10^{-6} \Sigma_f \bar{\phi}_f(x), \text{ (BTU/hr ft}^3\text{)} \quad (1)$$

where:

Σ_f = macroscopic fission cross section

$\phi_f(x)$ = mean thermal neutron flux at x

It was shown that:

$$\bar{\phi}_f(x) = 0.700 \phi_\infty(x) \quad (2)$$

where ϕ_∞ = unperturbed thermal neutron flux. Therefore, taking

$\Sigma_f = 0.496 \text{ cm}^{-1}$, it is seen that:

$$Q_f(x) = 1.15 \times 10^{-6} \phi_\infty(x) \quad (3)$$

Equation (3) is plotted in Figure 8.

B. Heat Flow per Unit Length

It was shown in a previous safeguards analysis* that the gamma-heating within the capsule is negligible when compared to the fission heating. Therefore, the gamma-heating contribution has been neglected in this calculation.

The heat flow per unit length at any axial position is given by equation (4).

$$q(x) = r_f^2 Q_f(x) \quad (4)$$

* WANL-TME-561

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Figure 8

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where:

$q(x)$ = heat flow per unit length at x

r = radius of fuel pellet

$Q_f(x)$ = fission heating rate density at x , BTU/(hr)(ft³)

By applying equation (3) and taking $r_f = 0.024$ ft. it is seen that:

$$q(x) = 2.08 \times 10^{-9} \phi_{00}(x), \text{ (BTU/hr ft).} \quad (5)$$

Equation (5) is plotted in Figure 9.

C. Film Coefficient

The film coefficient for water is given by Glasstone* as

$$h = 170 (1 + 10^{-2}T - 10^{-5}T^2) V^{0.8}/D_e^{0.2} \quad (6)$$

where:

h = film coefficient, (BTU/hr ft²F°)

T = film temperature, (°F)

V = coolant velocity, (ft/sec)

D_e = hydraulic diameter of the annulus, (in)

By taking $D_e = 0.160$ in. and $T = 180^\circ\text{F}$ it is seen that:

$$h = 6.08 \times 10^2 V^{0.8} \quad (7)$$

Equation (7) is plotted in Figure 10.

D. Temperature Drop Across Each Region

1. Fuel

The temperature drop across the fuel at any axial position is given by equation (8).

* S. Glasstone, "Principles of Nuclear Reactor Engineering", Van Nostrand (1955).

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Figure 9

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Figure 10

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$$\Delta T_f(x) = Q_f(x) r_f^2 / 4 k_f \quad (8)$$

where k_f = thermal conductivity of the fuel.

But,

$$Q_f r_f^2 = q / \pi$$

and therefore,

$$\Delta T_f(x) = q(x) / 4 \pi k_f \quad (9)$$

By applying equation (5) and taking $k_f = 18$ BTU/hr ft F° , it is seen that:

$$\Delta T_f(x) = 9.20 \times 10^{-12} \phi_\infty(x) \quad (10)$$

Equation (10) is plotted in Figure 11.

2. Graphite Sleeve

The temperature drop across the graphite sleeve at any axial position is given by equation (11).

$$\Delta T_{gr}(x) = q(x) \ln(r_o/r_i) / 2 \pi k_{gr} \quad (11)$$

where: r_o = outer radius of the sleeve

r_i = inner radius of the sleeve

k_{gr} = thermal conductivity of the graphite

By applying equation (5) and taking:

$$r_o = 0.920 \text{ in.}$$

$$r_i = 0.289 \text{ in.}$$

$$k_{gr} = 20 \text{ BTU/hr ft } F^\circ$$

it is seen that:

$$\Delta T_{gr}(x) = 1.92 \times 10^{-11} \phi_\infty(x) \quad (12)$$

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Equation (12) is plotted in Figure 11.

3. Radiation Gap

The inside of the capsule will be under vacuum so that all heat transfer across the gap is by radiation. Therefore, the temperature drop across the gap can be calculated using equation (13).

$$q(x) = 2 r_i F_{\epsilon} (T_i^4 - T_o^4), \quad (13)$$

where:

r_i = inner radius of the gap

T_i = temperature at the inside of the gap

T_o = temperature at the outside of the gap

$\sigma = 1.714 \times 10^{-8} \text{ BTU/ft}^2 \text{ hr } ^\circ\text{R}^4$

and F_{ϵ} is defined by the equation:

$$F_{\epsilon} = \left[\epsilon_i^{-1} + (r_o/r_i)(\epsilon_o^{-1} - 1) \right]^{-1}$$

where ϵ = emmissivity of the surface in question and

r_o = outer radius of the gap.

By taking $\epsilon_i = \epsilon_o = 0.98$

$r_i = 0.920 \text{ in.} = 0.077 \text{ ft.}$

$r_o = 0.969 \text{ in.,}$

by applying equation (5) and by assuming that $200^\circ\text{C} \leq T_i \leq 300^\circ\text{C}$ is is seen that:

$$\left\{ \left[3.34 \times 10^{11} + 2.61 \phi_{\infty} \right]^{\frac{1}{4}} - 100 \right\} \leq \Delta T_{gp} \leq \left[3.34 \times 10^{11} + 2.61 \phi_{\infty} \right]^{\frac{1}{4}} \quad (14)$$

The limits of equation (14) are plotted in Figure 11.

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Figure 11

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4. Stainless Steel Can

The temperature drop across the stainless steel can at any axial position is given by equation (15).

$$\Delta T_s(x) = q(x) \ln(r_o/r_i) / 2\pi k_s \quad (15)$$

where:

r_o = outer radius of the can

r_i = inner radius of the can

k_s = thermal conductivity of the stainless steel

By applying equation (5) and taking

$r_o = 1.00$ in.

$r_i = 0.969$ in.

$k_s = 9.2$ BTU/hr ft F°

it is seen that

$$\Delta T_s(x) = 1.07 \times 10^{-12} \phi_\infty(x) \quad (16)$$

Equation (16) is plotted in Figure 11.

5. Temperature Drop Across the Film

The temperature drop across the film at any axial position is given by equation (17).

$$\Delta T_{flm}(x) = q(x) / 2\pi r h, \quad (17)$$

where r = radius of the stainless steel can

h = film coefficient

By applying equation (5) and taking $r = 0.0833$ ft. it is seen

$$\text{that: } \Delta T_{flm}(x) = 3.98 \times 10^{-9} \phi_\infty(x) / h \quad (18)$$

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Equation (18) is plotted for various flow rates in Figure 11.

E. Bulk Temperature Rise in the Coolant

The incremental increase in the coolant temperature as it flows through the annulus is given by equation (19).

$$dT(x) = -q(x) dx/w c_p \quad (19)$$

where w = mass flow rate

c_p = specific heat of the coolant

In (19) the negative sign is taken because the origin of the system is placed at the coolant exit.

It is assumed that the flux distribution is that of the cycle average and can be described by equation (20).

$$\phi_{\infty}(x) = 1.1 \times 10^{14} \cos(0.077 x) \quad (20)$$

where $x = 0$ is taken at the flux peak which is 14 inches from the bottom of the core.

From equation (5) it is seen that

$$q(x) = 1.73 \times 10^{-10} \phi_{\infty}(x), \text{ (BTU/hr in)} \quad (21)$$

By combining equations (19), (20), and (21) and integrating over the effective four inches of capsule length it is seen that

$$\int_{T_i}^{T_B(x)} dT = - \frac{1.90 \times 10^4}{W c_p} \int_{x+4}^x \cos(0.077 x) dx \quad (22)$$

where

$T_B(x)$ = the bulk temperature rise in the coolant when the first

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fuel pellet is placed at x

T_i = inlet water temperature.

Taking $T_i = 100^\circ\text{F}$

$$C_p = 1 \text{ BTU/lb hr}$$
$$W = 5.01 \times 10^2 \text{ f lb/hr}$$

f = flow rate in gpm

it is seen that:

$$T_B(x) = 110 + 1.5 \times 10^2 \cos(0.077x + 0.154)/f \quad (23)$$

Equation (23) is plotted for various flow rates in Figure 12.

Figure 12

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Appendix II - Calculations for the Hydraulic Analysis

A. Pressure Drop in Flexible Metal Hose

According to the supplier of the flexible metal hose the pressure drop per length of hose for 20 gpm water is 1.6 psi/ft. The overall length of hose is 44 feet. Therefore,

$$P(\text{hose}) = (1.6)(44) = 70.4 \text{ psi}$$

B. Pressure Drop Resulting from Expansion into the Capsule

$$\Delta P_e = k_e V_1^2 \rho / 2 g,$$

where:

$$k_e = [1 - (D_1/D_2)^2]^2$$

D_1 = Diameter of smaller channel

D_2 = Diameter of larger channel

V_1 = Fluid velocity in smaller channel

g = Acceleration due to gravity

ρ = Fluid density

Taking:

D_1 = 0.75 inches (nominal)

D_2 = 2.10 inches

V_1 = 864.5 ft/min (20 gpm)

g = 1.15×10^5

ρ = 62.4 lb/ft³

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Then,

$$\Delta P_e = 1.08 \text{ psi}$$

C. Pressure Drop Resulting from Contraction into the Coolant Annulus

$$\Delta P_c = k_c V_2^2 \rho / 2 \text{ g,}$$

where:

V_2 = coolant velocity in annulus

$k_c = k_c (D_2/D_1)$

D_2 = hydraulic diameter of annulus

D_1 = diameter of larger channel

Taking

$D_2 = 0.160 \text{ inches}$

$D_1 = 2.1 \text{ inches}$

$k_e = 0.50$

$V_2 = 738$

then

$$\Delta P_c = 0.513 \text{ psi}$$

D. Pressure Drop Resulting from Flow Through Annulus

$$\Delta P_f = f' \rho V^2 l / 2 \text{ g D}$$

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where:

$$f' = \text{friction factor} = 0.079 \text{ Re}^{-0.25}$$

$$\text{Re} = \text{Reynolds number}$$

$$= DV\rho/u$$

$$V = \text{Fluid velocity}$$

$$l = \text{length of channel}$$

$$g = \text{acceleration due to gravity}$$

$$D = \text{hydraulic diameter of channel}$$

$$u = \text{coolant viscosity}$$

Taking

$$D = 0.013 \text{ ft.} = 0.160 \text{ inches}$$

$$V = 738 \text{ ft/min} = 4.43 \times 10^4 \text{ ft/gr (20 gpm)}$$

$$\rho = 62.4 \text{ lb/ft}^3$$

$$u = 1.65 \text{ lb.hr ft}$$

$$l = 0.671 \text{ inches}$$

then

$$\text{Re} = 2.17 \times 10^4$$

$$f' = 6.53 \times 10^{-3}$$

and

$$\Delta P_f = 1.38 \text{ psi}$$

E. Pressure Drop Resulting from Expansion into the Trail Cable Facility

$$\Delta P_e = k_e V_1^2 \rho / 2 g$$

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where:

$$k_e = [1 - (D_1/D_2)^2]^2$$

D_1 = hydraulic diameter of annulus

D_2 = diameter of Trail Cable Facility

V_1 = coolant velocity in annulus

Taking

$$D_1 = 0.160 \text{ inches}$$

$$D_2 = 2.50 \text{ inches}$$

$$V_1 = 738 \text{ ft/min}$$

$$g = 1.15 \times 10^5 \text{ ft/min}^2$$

then

$$\Delta P_e = 1.02 \text{ psi}$$

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Appendix III - Calculations for the Stress Analysis

A. Thermal Stress

According to Timoshenko* the tangential and axial thermal stresses at the inner and outer surfaces of a thin wall, hollow cylinder are respectively,

$$(\sigma_{\theta})_i = (\sigma_z)_i = -\alpha E (T_i - T_o) (1 + m/3) / 2 (1 - \nu) \quad (1)$$

and

$$(\sigma_{\theta})_o = (\sigma_z)_o = \alpha E (T_i - T_o) (1 - m/3) / 2 (1 - \nu) \quad (2)$$

where

σ_{θ} = tangential stress (tensile if positive)

σ_z = axial stress (tensile if positive)

α = coefficient of linear thermal expansion

E = modulus of elasticity

T = temperature

r = radius

ν = Poisson's ratio

$$(1 + m) = (r_o / r_i)$$

It was shown that (see thermal analysis)

$$(T_i - T_o) = 1.07 \times 10^{-12} \phi_{\infty}.$$

* S. Timoshenko, "Theory of Elasticity", McGraw-Mill (1934)

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Therefore,

$$(\epsilon_{\theta})_i = (\epsilon_z)_i = 1.07 \times 10^{-12} \rho_d E (1 + m/3)/2 (1-\nu), \quad (3)$$

and

$$(\epsilon_{\theta})_o = (\epsilon_z)_o = 1.07 \times 10^{-12} \rho_d E (1 - m/3)/2 (1-\nu). \quad (4)$$

B. Stress Resulting from Hydrostatic Pressure

It is assumed that:

1. The capsule is under 30 feet of water
2. Water is delivered at 20 gpm so that the operational pressure is 47.7 psi (see hydraulic analysis)
3. The inside of the capsule is under vacuum.

Therefore, the resulting hydrostatic pressure acting upon the inner can is:

$$P_{\text{total}} = 27.6 + 47.7 = 75.3 \text{ psi.}$$

P_{total} causes a tangential compressive stress given by (5).

$$\epsilon'_{\theta} = -P_{\text{total}} r/t, \quad (5)$$

where:

r = radius of can

t = wall thickness

C. Total Stress

The total stress acting on the inner can is the sum of the thermal stress and the stress resulting from the hydrostatic pressure. Therefore, adding (5) to (3) and (4),

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$$(\epsilon'_{\theta})_i = -1.07 \times 10^{-12} \phi_{\infty} \alpha E (1+m/3)/2 (1-\nu) -Pr/t \quad (6)$$

$$(\epsilon'_Z)_i = -1.07 \times 10^{-12} \phi_{\infty} \alpha E (1+m/3)/2 (1-\nu) \quad (7)$$

$$(\epsilon'_{\theta})_o = 1.07 \times 10^{-12} \phi_{\infty} \alpha E (1-m/3)/2 (1-\nu) -Pr/t \quad (8)$$

$$(\epsilon'_Z)_o = 1.07 \times 10^{-12} \phi_{\infty} \alpha E (1-m/3)/2 (1-\nu) \quad (9)$$

Taking

$$E = 2.8 \times 10^7 \text{ psi}$$

$$\alpha = 9.5 \times 10^{-6} (\text{°F})^{-1}$$

$$\nu = 0.270$$

$$r_i = 0.969 \text{ in}$$

$$r_o = 1.00 \text{ in}$$

$$t = 0.031 \text{ in}$$

it is seen that

$$(\epsilon'_{\theta})_i = -1.97 \times 10^{-10} \phi_{\infty} -2.43 \times 10^3 \quad (10)$$

$$(\epsilon'_Z)_i = 1.97 \times 10^{-10} \phi_{\infty} \quad (11)$$

$$(\epsilon'_{\theta})_o = 1.93 \times 10^{-10} \phi_{\infty} -2.43 \times 10^3 \quad (12)$$

$$(\epsilon'_Z)_o = 1.93 \times 10^{-10} \phi_{\infty} \quad (13)$$

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