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TECHNICAL DATA RECORD

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S. R. Fields *SR Fields* 727 75 HQ 5

GO NO. 7622

TITLE Thermo-Physics Technical Note No.: 29
ASYMMETRIC HEAT TRANSFER IN A SNAP 2 FUEL ELEMENT

S/A NO. 1341

TWR 52494

PROGRAM

SUBACCOUNT TITLE

SNAP 2

Thermal and Hydraulic Analysis

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STATEMENT OF PROBLEM

Calculate the asymmetric temperature distributions and heat fluxes of a SNAP 2 fuel rod due to the non-circular coolant channel. Calculate the convective heat transfer coefficient.

ABSTRACT:

A method is presented for the determination of the steady-state asymmetric temperature distributions and heat fluxes, in a SNAP 2 fuel element, due to the influence of the non-circular coolant channel. The results obtained and presented include not only the temperatures and heat fluxes but also convective heat transfer coefficients and an estimate of the reactor UA.

The temperatures are presented in both map and graph form. A plot of the heat fluxes reveals a significant variation over the surface of the fuel element. Calculated convective heat transfer coefficients give an average value which is substantially less than those obtained using the Lubarsky-Kaufman and Sletten correlations. A value of 0.8 KW/°F was estimated for the reactor UA which compares favorably with one previously reported. (Reference 7).

ACKNOWLEDGEMENTS

The successful completion of this study has been due, in large part, to the excellent assistance and important contributions of A. W. Barsell and M. A. McCoy.

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INTRODUCTION

The purpose of this report is to present a method of analysis and results of a study to determine the steady-state asymmetric temperature distributions and heat fluxes in a SNAP 2 fuel element, due to the non-circular coolant channel, at turbulent flow conditions. In addition, convective heat transfer coefficients determined from the results and an estimated value of UA for the reactor are presented.

This study was made to obtain a more realistic estimate of the fuel element temperature distributions and heat fluxes than those made without consideration of the effects of the non-circular coolant channel. Extremely important and useful by-products of the study are the calculated values of convective heat transfer coefficients and reactor UA.

The methods developed in this study and some of the results are applicable to the SNAP 10A and 8 reactors as well as for SNAP 2.

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THEORY AND METHODS

A model representing a portion of the fuel element and coolant channel is shown in Figures 1 through 10. Because of the complex shape of the model and the future possibility of incorporating temperature varying physical properties of the fuel-moderator material and coolant, the model was simulated on the Thermal Analyzer Program (TAP). A description of TAP and instructions for its use may be found in Reference (1) and will not be repeated here. Two variations of the original TAP code were used and will be discussed later.

The TAP simulation of the model was based upon differential equations which describe the steady-state heat transfer process in the fuel-moderator portion of the element and in the coolant channel. These differential equations are:

$$\frac{\partial^2 t}{\partial z^2} + \frac{\partial^2 t}{\partial y^2} + \frac{q_v}{k} = 0 \quad (1)$$

for the fuel-moderator portion of the element and

$$\frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial y^2} = \frac{\rho u C}{K_r} \frac{\partial T}{\partial x} \quad (2)$$

for the coolant channel. All terms in the equations presented are defined in the section on Nomenclature of Terms.

Equations (1) and (2) may be approximated by finite-difference methods and reduced to forms compatible with the thermal-electrical analogy upon which TAP is based. The resulting equations are:

$$\begin{aligned} & k \frac{\Delta z}{\Delta y} (t_{y,m+1} - t_{m,n}) + k \frac{\Delta z}{\Delta y} (t_{y,m-1} - t_{m,n}) \\ & + k \frac{\Delta y}{\Delta z} (t_{z,n+1} - t_{m,n}) + k \frac{\Delta y}{\Delta z} (t_{z,n-1} - t_{m,n}) \\ & + q_v \Delta x \Delta y \Delta z = 0 \end{aligned} \quad (3)$$

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for the fuel element and

$$\begin{aligned} K_T \frac{\Delta z}{\Delta y} (T_{y,m+1} - T_{m,n}) + K_T \frac{\Delta z}{\Delta y} (T_{y,m-1} - T_{m,n}) + K_T \frac{\Delta y}{\Delta z} (T_{z,n+1} - T_{m,n}) \\ + K_T \frac{\Delta y}{\Delta z} (T_{z,n-1} - T_{m,n}) = (\rho u C)_{m,n} \frac{\Delta y \Delta z}{\Delta x} (T_{x,o} - T_{x,i}) \\ = 2(\rho u C)_{m,n} \frac{\Delta y \Delta z}{\Delta x} (T_{m,n} - T_{x,i}) \end{aligned} \quad (4)$$

for the coolant. The right-hand side of equation (4) is a "dissipation" term. The dissipation of heat takes place with a "sink" temperature which is the coolant temperature at the inlet to the increment.

For each axial increment, inlet coolant temperatures are obtained from the results of calculations on the preceding increment. The increment inlet temperatures are then used in the coolant network from which the axial mean coolant temperatures are calculated by the TAP code. The outlet temperatures (inlet temperatures for the following increment) are then calculated by assuming a linear relationship in the inlet-to-outlet temperature rise for each increment separately. Thus

$$T_o = 2 T_m - T_i \quad (5)$$

For TAP-3 calculations dummy nodes are assigned to increment outlet points, the temperatures of which are computed for each iteration according to the algebraic function (5). Since this algebraic function is not available in the TAP-2 code, a secondary circuit network was designed to calculate the outlet temperatures T_o for each iteration without affecting the primary network. This secondary network is illustrated below

During the course of this study, steady development of the TAP program was in progress. In the earlier phases of the study TAP-2 was used and, in the latter phases, the latest and best version, TAP-3, became available. The final phase of the study was carried out using both TAP-2 and TAP-3 which provided an opportunity for comparing the two versions. In this final phase, TAP-2 computations were obtained for

the first three axial increments (from the bottom of the fuel element). These calculations were then repeated using the revised TAP-3 program and the results were compared with those obtained using TAP-2. It was found that

1. The final temperatures agreed very well for each increment.
2. The number of iterations needed for convergence was about the same in both cases.
3. The computer running time was shorter in the TAP-3 determinations (approximately 8 minutes per increment compared to about 12 minutes per increment).

To conserve computer time, the TAP-3 program was used for the calculations for the remaining increments. It was possible to compute two increments in one continuous run since TAP-3 had been designed for such successive interdependent problems. This transition was made by transferring the final outlet temperatures for the first increment to the inlet temperatures for the second and correcting the axial power distribution factor (derived from equation (15)).

The coolant channel network is connected to the fuel moderator network by a "boundary" network which includes the hydrogen gap between the fuel and cladding, hydrogen barrier, and cladding. All other boundaries are adiabatic due to symmetry. A typical link in the "boundary" network is illustrated in the following sketch. In this

sketch, conduction paths are denoted by K and radiation paths by R. The heat transferred along this path may be expressed as

$$Q = \left[\frac{K}{l} + h_r F \right] A (t_1 - t_2) = \left(\frac{K}{l} \right) A (t_2 - t_3) \quad (6a)$$

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coolant thermal conductivity for turbulent flow may be expressed as

$$K_T = (K + \rho C \epsilon) \quad (10)$$

where the eddy diffusivity for heat transfer is obtained from

$$\epsilon = n^2 u y \left[1 - \exp\left(-\frac{n^2 u y}{r}\right) \right] \quad (\text{Reference 4}) \quad (11)$$

for the laminar and buffer zones of the boundary layer and from

$$\epsilon = \frac{\mu^2 (du/dy)^3}{(d^2u/dy^2)^2} \quad (\text{Reference 4}) \quad (12)$$

for the turbulent core.

A convective heat transfer coefficient may be calculated for each length increment from the results of the study by the equation

$$h = \frac{Q}{A (T_{sm} - T_{cm})} \quad (13)$$

In this equation, T_{sm} is the mean rod surface temperature and T_{cm} is the integrated average coolant temperature.

The variation of heat flux along the surface of the fuel element cladding may be obtained by solving the equation

$$\frac{Q}{A} = \left(\frac{k}{l} \right)_{\text{cladding}} (t_4 - t_5) \quad (14)$$

for the typical link as shown in the sketch on page 5.

A value of UA, the overall conductance for the transfer of heat from the fuel to the coolant, was estimated for the reactor from temperatures calculated for the fuel element-coolant channel model. The average temperatures of the fuel element and coolant were obtained from the temperature distributions and the difference between these temperatures, along with the known value of reactor power, was used to estimate a value of UA.

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DATA AND ASSUMPTIONS

The data and assumptions presented here form the bases of the study and define the analytical model used; consequently, the results of the study are valid for the model and are, at best, an approximation of the actual physical case.

The data used in the study, based on the SNAP 2 reactor, are

1. Coolant	NaK-78
2. Inlet coolant temperature, °F	1000
3. Coolant flow rate, lb/min (Reference 3)	80.0
4. Total reactor power, KW (Reference 3)	53.5
5. Coolant flow rate in the central channel, lb/min (Reference 3)	1.38
6. Active fuel element length, inches (Reference 3)	12.25
7. Clad fuel element diameter, inches	1.25
8. Cladding thickness, inch	0.015
9. Thickness of gap between fuel element and cladding, inch	0.0015
10. Average coolant velocity in a channel ft/sec	0.983

Differences between the actual fuel element and the model used are due to the following assumptions:

1. All physical properties were assumed to be constant. The physical properties used are:
 - a. Thermal conductivity, B/hr ft °F
 - fuel 15.0
 - cladding 16.0
 - hydrogen 0.25
 - coolant 15.0
 - b. Specific heat of coolant = 0.209 B/lb °F
 - c. Density of coolant = 0.0264 lb/in³.
2. A heat transfer coefficient for radiative heat transfer

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between fuel element and barrier was assumed to be 32.0 B/hr ft²°F for surface temperatures near 1200°F. Combined with emissivities 0.8 for both surfaces, this coefficient produced a conductance which was negligible compared to that for conduction through the gas in the gap.

3. The fuel element spacing is 1.257 inches.
4. The gap between the fuel element surface and cladding is filled with hydrogen.
5. The resistance of the barrier to heat flow was neglected.
6. The power variation axially in the fuel element was computed from:

$$g_v = g_{v0} \cos(1.479 - 0.241x) \quad (\text{Reference 3})$$
$$(0 \leq x \leq 12.25) \quad (15)$$

where g_{v0} = the average heat generation, H/tL^3

7. The flow of coolant was assumed to be steady and with no velocity components normal to the coolant channel axis.
8. In a length increment of the coolant channel, the dissipation of heat takes place with a "sink" temperature which is the coolant temperature at the inlet to the increment (the outlet temperature of the preceding increment).
9. If the coolant channel length is divided into sufficiently small increments, the outlet coolant temperature of the small increment may be expressed by equation (5).
10. A source temperature of 1×10^9 °F, along with an appropriate admittance, was used for some nodes to provide a heat input equivalent to that generated.
11. The volumetric heat generation in the cladding was assumed to be the same as that in the fuel element.
12. Axial heat conduction in the fuel element was neglected.
13. Turbulent flow in the channels was assumed since it was felt that the lower or inlet grid assembly acts as a turbulence promoter.

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DISCUSSION OF RESULTS

The results of the study are presented in several different forms. Temperature distributions are presented in map form, for each length increment, in Figures 1 through 10. Some of the temperatures are re-plotted in graph form in Figures 11, 12, 13 and 14. Figure 15 is a plot of the ratio of the local to average heat flux at the surface of the fuel element as a function of radial angle. Figure 16 is a plot of the calculated convective heat transfer coefficient as a function of axial length. The value of the calculated overall heat transfer conductance, UA , is presented and discussed later in the text of this section.

The Reynolds number for flow in the SNAP 2 reactor was calculated to be about 4900 at design conditions. The value falls very close to the so-called "transition region" between the laminar and turbulent regimes on a friction factor--Reynolds number plot, however, it was assumed in this study that turbulent flow is assured because of the probable promotion of turbulence by the lower or inlet grid assembly. The assumption of turbulent flow led to the use of the appropriate velocity distribution from Reference (2) and the use of equations (10), (11) and (12).

A. Temperature Distributions

The temperature maps (Figures 1 - 10) present an interesting pattern which indicates a bending of heat flow toward that portion of the coolant channel which contains the more rapidly moving coolant. The temperatures along the peripheral surface of the fuel element vary significantly, with the hottest spot occurring at the point of closest proximity to the neighboring element. However, the magnitude of the temperature at this point is not serious.

The variation of temperature around the surface of the fuel element causes one to think of possible resultant thermal stresses in the element, wrinkling of the cladding and cracking of the barrier. This, of course would be more serious in SNAP reactors operating at higher powers. These secondary effects have not been evaluated as part of this study but are being considered for possible future studies.

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The asymmetric temperature distributions shown on the temperature maps would also cause an asymmetric flow and distribution of hydrogen in the rod. This situation may be evaluated in future studies since methods are now under development by the Thermo-Physics Unit for the determination of the hydrogen redistribution in complex shapes and under the influence of unusual temperature distributions.

B. Local Heat Fluxes at the Fuel Element Surface

The variation of the local heat flux at the fuel element surface is presented in Figure 15 and further illustrates the flow of heat towards that portion of the coolant channel which contains the more rapidly moving coolant. The spread of the plotted points on Figure 15 is not unlike that expected from experimental data and is unlike that expected from calculated results. The heat fluxes were calculated using equation (14) which contains a temperature difference term. Unfortunately, the temperatures involved in this term are high values and the differences between the values are very small numbers, consequently, the chances for computational errors to be magnified out of all proportion are quite good. The TAP code, justifiably so, does not yield temperatures with large decimal fractions for the purpose of taking such small differences. Even with the spread of points due to the computational errors the heat flux plot of Figure 15 reflects the variation at the fuel element surface. An upper and lower limit is shown in Figure 15 along with a line through the average points. The latter curve is particularly useful, when reduced to equation form, in providing a boundary condition for differential equations describing the heat transfer in the fuel element cross-section. This approach to the heat transfer analysis of the fuel element could save many hours of digital-computer time when used for certain design problems.

The value of $(Q/A)_{ave}$ is defined as that value for a fuel element under symmetrical heat removal conditions, i.e., an ideal situation where the coolant channel is considered to be distributed over the surface of the fuel element as an annular shell. It is interesting to note that the local heat flux for that portion of the fuel element adjacent to the highest velocity coolant is about a factor of two greater than the heat flux for a symmetrically cooled rod while

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at the smallest end of the channel cross-section the flux is nearly zero.

C. Heat Transfer Coefficients

Heat transfer coefficients were determined for the transfer of heat by convection from the clad fuel element surface to the coolant. These coefficients were calculated from the results of the study using equation (13). The calculated values are plotted in Figure 16 as a function of the distance from the bottom of the fuel element. An average value of the coefficient, corresponding to an average coolant temperature of 1100°F, is 1500 B/hr ft²°F. This may be compared with a value of 2780 B/hr ft²°F obtained from the Lubarsky-Kaufman correlation (Reference 5) and a value of 5200 B/hr ft²°F obtained from the correlation recommended by Sletten (Reference 6).

The Lubarsky-Kaufman correlation is

$$Nu = 0.625 Pe^{0.4} \quad (16)$$

and the correlation recommended by Sletten is

$$Nu = 4.0 + 0.024 Pe^{0.8} \quad (17)$$

These correlations have been in common use even though they are not recommended for Peclet numbers (Pe) as low as those determined for the SNAP 2 reactor (e.g., in this study Pe was calculated to be 26.6). Figure 17 is a plot of Nusselt number (Nu) vs Peclet number for liquid metals and shows experimental results obtained by various investigators. A point representing the calculated value of heat transfer coefficient (Nu = 1.25, Pe=26.6) is shown to be in good agreement with the limited data reported.

It is proposed later in this report that calculations similar to those of the present study, modified to exclude the fuel element, be made to determine the heat transfer coefficient for the SNAP 2 coolant channel at various temperatures, flows and powers. These calculations would provide a correlation to be used in future SNAP 2 design calculations. A similar correlation could be devised for the SNAP 8 reactor.

D. Overall Reactor Heat Transfer Conductance, UA

A value of 0.8 KW/°F was estimated for UA, the overall conductance for the transfer of heat from the fuel to the coolant, using the temperatures calculated for the model and the specified reactor power of 53.5 KW. This estimated value of UA is subject to some error since the temperatures used were those calculated for the central fuel element

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and channel and not those representing the average fuel element in the reactor. Podeweltz (Reference 7) states that UA rises rapidly to a value of approximately $0.6 \text{ KW}^\circ\text{F}$ at 1250°F when fuel temperatures are increased beyond 1000°F . This value was apparently experimentally derived from S2DR data at 68 lb/min total reactor flow as compared to 80 lb/min used for SNAP 2 in the present study. Considering the difference in active fuel element length in the S2DR compared to that in the SNAP 2 reactor the two values of UA appear to be in good agreement.

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CONCLUSIONS AND RECOMMENDATIONS

An effective method has been devised for the analysis of the asymmetric heat transfer in a SNAP 2 fuel element and adjacent coolant channel due to the non-circular cross-section of the coolant channel. The method has been used to calculate the asymmetric temperature distributions in the fuel element and coolant channel, to determine the coefficient for convective heat transfer from the fuel element surface to the coolant, and to determine the variation of the heat flux around the surface of the fuel element.

The method devised may be used for the analysis of the SNAP 8 reactor as well as for the SNAP 2/10A configuration.

Asymmetric heat transfer in the fuel element causes a variation of temperature around the surface of the fuel element which might have serious consequences in the present SNAP 2 reactor and would most certainly be detrimental in SNAP reactors operating at higher powers. Some of these possible consequences are excessive thermal stresses in the fuel, wrinkling of the cladding and cracking of the barrier. It is recommended that the temperature distributions presented in this report now be used to evaluate these possible consequences and an additional effect on the steady-state hydrogen redistribution. The Thermo-Physics Unit has developed a method for evaluating the effect on the hydrogen redistribution (Reference 8) and is prepared to put under development a method, now in the conceptual stage, for determining thermal stresses in complex shapes subjected to unusual temperature distributions.

The highest temperature on the surface of the fuel element occurs at the point of closest proximity to the neighboring element. However, the magnitude of the temperature at this point is not serious for the SNAP 2 reactor at the specified values of power and flow rate.

The coefficient for convective heat transfer from the fuel element surface to the coolant, h , obtained as a by-product of the temperature determinations, indicates that the two correlations used in the past for the determination of such coefficients cannot be used for the flow channels in the SNAP reactors. These correlations, the Lubarsky-Kaufman and Sletten correlations, give values of h that are higher than those determined by factors of about 2 and 3.5, respectively.

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It is recommended that a variation of the present study be made to determine values of h for the SNAP 2/10A and 8 reactors for various temperatures, flow rates, rod spacing, etc. This study would be limited to the appropriate coolant network with the fuel element simulated by a heat flux distribution, such as that of Figure 15, applied at the surface. (In the case of the SNAP 8 reactor, a preliminary determination of the velocity distributions in the coolant channel would be necessary.) From the results of a study of this type a correlation for h could be synthesized.

The variation of the heat flux around the surface of the fuel element is presented in Figure 15. It was originally planned that an equation be fitted to the curve shown so that the heat flux variation could be expressed in a form more suitable for its use as a boundary condition in future mathematical descriptions of the heat transfer process in a fuel element. A shortage of funds prevented the completion of this phase of the study, therefore, it is recommended that funds be provided to complete the work.

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NOMENCLATURE OF TERMS

1. Definition of Terms

- A = Fuel element surface area, L^2 .
- C = Specific heat of the coolant, H/MT.
- f = Combined emissivity and shape factor.
- h = Heat transfer coefficient for convection, H/tL^2T .
- h_r = Heat transfer coefficient for radiation, H/tL^2T .
- k = Thermal conductivity of the fuel, H/tLT.
- K = Molecular thermal conductivity of the coolant, H/tLT.
- K_T = Total thermal conductivity of the coolant, H/tLT.
- l = Heat transfer path length, L.
- n = Constant, experimentally determined = 0.124.
- Nu = Nusselt's number.
- Pe = Peclet number = RePr.
- Pr = Prandtl number.
- q_v = Volumetric heat generation in the fuel element, H/tL^3 .
- q_{vo} , the average heat generation.
- Q = The rate of heat flow passing through the fuel element surface, H/t.
- Q_g = The total amount of heat generated at a node, H/t.
- Re = Reynold's number.
- t = Fuel element temperature, T.
- T = Coolant temperature, T.
- u = Z-component of the coolant velocity, i.e., the velocity parallel to the channel centerline, L/t.
- U = Overall coefficient for the transfer of heat from the fuel to the coolant, H/tL^2T .
- χ = Variable distance along the length of the coolant channel, L.
- y and z = Variable distances in the coolant channel cross-section, L.
- y = Normal distance from coolant channel wall in equations (10) and (11), L.

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Y = Thermal admittance (i.e., the reciprocal of thermal resistance) Tt/H .

ϵ = Coefficient of eddy diffusivity, L^2/t .

$\mathcal{H}$ = Karman constant, experimentally determined. = 0.36

ν = Kinematic viscosity, L^2/t .

ρ = Density* of the coolant, M/L^3 .

2. Definition of Subscripts

cm Denotes integrated average coolant temperature.

g Denotes heat input due to heat generation.

i Inlet value.

m Mean value.

m Nodal designation in y - direction.

n Nodal designation in z - direction.

o Denotes outlet temperature or average volumetric heat generation value.

sm Denotes mean surface temperature.

T Total.

V Denotes a value per unit volume.

W Denotes temperature of coolant at the wall.

X Denotes X - direction.

y Denotes Y - direction.

z Denotes Z - direction.

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FIGURE 1

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

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DISTANCE FROM BOTTOM OF FUEL = 0.6125"

INCREMENT 1

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FIGURE 2

STEADY - STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 1.8375"

INCREMENT 2

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FIGURE 3

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 3.0625"
INCREMENT 3

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FIGURE 4

STEADY - STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 4.2875"

INCREMENT 4

0371281030

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Classification	RD/DI	Group
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FIGURE 5

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 5.5125"
INCREMENT 5

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FIGURE 6

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

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<i>S. Fields</i> Authorized Classifier Signature		Date: 12/3/63

DISTANCE FROM BOTTOM OF FUEL = 6.7375"
INCREMENT 6

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Classification	RD/DI	Group
J. R. Fields		Date: 12/31/63
Authorized Classifier Signature		

FIGURE 7

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 7.9625"
INCREMENT 7

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FIGURE 9

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

DISTANCE FROM BOTTOM OF FUEL = 10.4125
INCREMENT 9

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FIGURE 10

STEADY-STATE TEMPERATURES IN A SNAP-2 FUEL ROD AND COOLANT CHANNEL

Confidential RD	1	
Classification	RD/DI	Group
Date: 12/31/63
Authorized Classifier Signature		

DISTANCE FROM BOTTOM OF FUEL = 11.6375"
INCREMENT 10

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FIGURE II
COOLANT TEMPERATURE AS A FUNCTION OF AXIAL LENGTH

COOLANT TEMPERATURE - DEGREES F

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Classification: *Confidential* RD
Date: *12/1/62*
Signature: *[Signature]*
Group: *[Blank]*

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FIGURE 12
MAXIMUM FUEL ROD TEMPERATURE AS A FUNCTION OF AXIAL LENGTH

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FIGURE 3 - TEMPERATURE IN RADIAL CENTER OF CLADDING AS A FUNCTION OF RADIAL ANGLE

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FIGURE 14-FUEL SURFACE TEMPERATURE AS A FUNCTION OF RADIAL ANGLE

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RD/DI
Group

12/6/68
Name
Signature

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RATIO OF LOCAL TO AVERAGE HEAT FLUX AT THE SURFACE
OF A FUEL ROD AS A FUNCTION OF RADIAL ANGLE
(AVERAGE FOR ALL INCREMENTS)

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FIGURE 15

FIGURE 16
CONVECTIVE HEAT TRANSFER COEFFICIENT AS A FUNCTION OF AXIAL LENGTH

BTU
/
SEC
/
IN²
/
(°F)

$$h = \frac{(Q/A)_{\text{AVE}}}{(T_{\text{GM}} - T_{\text{GM}})}$$

FLOW →

ENAP-2 FUEL ROD
1.25" O.D. X 12.25"

LENGTH

1.225

2.45

4.9

7.35

9.8

12.25

DISTANCE FROM BOTTOM OF FUEL ROD INCHES

FIGURE 17
~~Figure 17. Concluded.~~

(b) Re-evaluated data points.

Comparison of measured and predicted fully developed Nusselt numbers in round tubes with constant heat input to wall.

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