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TECHNICAL DATA RECORD

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TITLE

S/A NO 4410

Fuel Channel Variable Orifice Design

TWR 41913

RECOMMENDED FOR
OUTSIDE DISTRIBUTION

PROGRAM

SUBACCOUNT TITLE

☐ YES ☐ NO

ASCR

Sodium Cooled Reactor Design and Evaluation

SIGNATURE

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Determine the performance characteristics of variable fuel
channel orifice for the 360 Mwe ASCR

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ABSTRACT:

*
A design analysis of a variable adjustable orifice that can
be used on all fuel channels is presented. With an adjustment
range of 1/4 turn the flow can be controlled over the range
9.9 to 36.9 lb/sec with a constant sensitivity of 5.85F/deg. rot.
for $\Delta T = 400F$. Temperature sensitivity can be reduced by
increasing the adjustment range; a range of 3/8 turn will
reduce the sensitivity to less than 4F per degree rotation.
The orifice contraction coefficient must be determined exper-
imentally. Leakage flow through the annulus between the process
channel and the orifice extension tube has been taken into
account. A 1/32 inch wide annular clearance is the maximum
that can be tolerated to maintain control of the flow.

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NOMENCLATURE

A = Area, in²

To = outlet coolant temperature, F

Ti = inlet coolant temperature, F

W = coolant flow rate, lb/sec

Q = heat generation rate, Btu/sec

Cp = specific heat, Btu/lb F

Θ = position of orifice, degrees rotation

S = temperature sensitivity, F/degree rotation.

K = unit temperature sensitivity F/degree rotation/F.

η = total orifice adjustment range, degrees rotation

h = head loss, ft-lb/lb

B = head loss coefficient

V = velocity of coolant, ft/sec

p = pressure, psi

ρ = density, lb/ft³

C = orifice discharge coefficient

Cv = orifice discharge velocity coefficient

Cc = orifice discharge contraction coefficient

a = annulus thickness

SUBSCRIPTS

t = value in orifice tube ($d_t = 7.125"$)

o = value with orifice open or at outlet

c = value with orifice closed.

i = value at inlet

f = value in fuel channel

e = value at exit from fuel channel ($d_e = 4.125"$)

b = value due to turning coolant.

v = value at variable orifice

l = value due to leakage

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I. The Orifice Criteria

The power generation in a reactor fuel element is a function of its location in the core because of the spatial variation in neutron flux density and of time as a result of fuel burn-up. A uniform outlet coolant temperature, T_o , from all fuel elements is desirable and requires that the flow rates, W , be matched to the power generation, Q , in accordance with the relationship,

$$Q = WC_p (T_o - T_i) \quad (1)$$

This can be accomplished by providing a variable adjustable orifice in each fuel channel. The following criteria are arbitrarily specified.

1. The orifice shall be capable of controlling fuel channel exit temperature to within ± 10 F of the mixed mean outlet coolant temperature.
2. All orifices shall be identical and shall not require a gross fixed orifice sized for a particular channel.
3. The temperature sensitivity of the orifice shall be constant for a given core temperature change of the coolant, that is, equal adjustments shall produce equal changes in coolant temperatures over the entire flow range.

II. Flow Rate vs. Orifice Adjustment

The relationship between flow rate and orifice adjustment for a constant temperature sensitivity will now be developed. At any given heat generation rate Q , a fractional change in flow rate results in an equal but opposite fractional change in the outlet coolant temperature T_o , assuming the inlet coolant temperature T_i is maintained constant.

$$\frac{dW}{W} = - \frac{dT_o}{T_o - T_i} \quad (2)$$

An orifice which, for a given adjustment increment $d\phi$, produces proportional changes in the fractional flow rate, for any flow rate, will produce proportional changes in the fractional outlet temperature. A linear relationship between $d\phi$ and $\frac{dW}{W}$ will also result in linear relationship between $d\phi$ and $\frac{dT_o}{T_o - T_i}$. Thus

$$K d\phi = \frac{dW}{W} = - \frac{dT_o}{T_o - T_i} \quad (3)$$

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where K is a constant and,

$$\frac{dT_o}{d\theta} = -K (T_o - T_i). \quad (4)$$

The temperature sensitivity of the orifice has been defined as the rate of change of outlet coolant temperature with respect to orifice position,

$$S = \frac{dT_o}{d\theta}. \quad (5)$$

The required relationship between flow rate and orifice position is obtained by integrating the equation relating θ and W , given in equations (3). Thus

$$GW = e^{K\theta}$$

where G is an integration constant. Using the following boundary conditions,

1. $W = W_c$ when $\theta = 0$
2. $W = W_o$ when $\theta = n$,

$$W = W_c e^{\left(\frac{1}{n} \ln \frac{W_o}{W_c} \right) \theta} = W_c \left(\frac{W_o}{W_c} \right)^{\frac{\theta}{n}}, \quad (6)$$

where, W_c = minimum flow rate (orifice closed)

W_o = maximum flow rate (orifice open)

n = total orifice adjustment range

θ = orifice position (fraction of n).

Differentiating equation (6) with respect to θ ,

$$\frac{dW}{W} = \left(\frac{1}{n} \ln \frac{W_o}{W_c} \right) d\theta \quad (7)$$

from which

$$K = \frac{1}{n} \ln \frac{W_o}{W_c}$$

and

$$S = - \left(\frac{1}{n} \ln \frac{W_o}{W_c} \right) (T_o - T_i). \quad (8)$$

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The constant K , which is the unit temperature sensitivity, is plotted in Figure 1. It increases logarithmically as the ratio of range in flow rate, $\frac{W_o}{W_c}$, is increased, and decreases

linearly as the number of adjustment increments, n , is increased. Low sensitivity is desirable and can be achieved by reducing the flow range or by increasing the number of adjustment increments.

III. ASCR Orifice Data

The basic reference for the following data is an IOL dated September 18, 1962 to K. W. Foster from H. L. Sletten.

Radial power distribution

Peak to average	1.49
Peak to minimum	2.61

Design burnup, % peak power 30

Coolant flow rate range

Central position, lb/sec	36.9 to 25.8
Peripheral position, lb/sec	14.1 to 9.9

Coolant temperature

Outlet, F	1150
Inlet, F	750

Core pressure loss, psi 21

Max. velocity in fuel
channel, ft/sec

14.3

The range in fuel channel flow rate that must be controlled by the orifice is from $W_c = 9.9$ to $W_o = 36.9$ lb/sec. The ratio of range in flow rate is $\frac{W_o}{W_c} = 3.73$. The sensitivity

S is obtained from Figure 1. Assuming that orifice adjustment is limited to $1/4$ turn or 90° and that the smallest adjustment increment is 1° , the sensitivity will be 5.85 F per increment. The sensitivity can be reduced by using more adjustment increments, preferably with a greater total orifice adjustment. The relationship between flow rate and orifice position is expressed by equation (6) and is plotted in Figure 2. For the case, $n = 90$ equation (6) becomes,

$$W = 9.9 e^{0.01463\theta}$$

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The per cent change in flow rate per orifice adjustment increment is obtained from equation (7) and is simply 100 K or 1.463% for this case. The characteristics of the orifice discussed above may be summarized as follows: Opening the orifice by one adjustment increment (1° rotation) will increase the flow rate 1.463% and decrease the temperature 5.85°F when $\Delta T = 400^\circ F$.

IV. Pressure Loss Relationships

A. Flow Through Orifice

The pressure loss between the inlet and outlet plenums is 21 psi. It is equal to the sum of the following pressure or equivalent head losses. Refer to Figure 3 for ~~general~~ configuration of fuel channel outlet.

1. Entrance to fuel channel from inlet plenum.
2. Friction through fuel channel.
3. Exit from fuel channel.
4. Enlargement in orifice tube.
5. Turning of coolant into orifice.
6. Flow through orifice.
7. Exit from orifice into outlet plenum.

We will assume that the Reynolds numbers are high enough so that the head losses are proportional to the velocity head and that the coefficients, B, can be taken as constants. The total head loss across the core through the orifice can then be expressed by

$$h_l = B_f \frac{v_f^2}{2g} + B_e \frac{v_f^2}{2g} + B_b \frac{v_t^2}{2g} + B_v \frac{v_o^2}{2g} + B_o \frac{v_o^2}{2g} \quad (9)$$

where the subscripts describe the various head loss components (see nomenclature). Each of these terms will be examined individually.

The fuel channel loss includes the loss at the entrance and exit of the process tube. At maximum velocity this loss is expected to be equivalent to a pressure loss of 17.5 to 19 psi. Setting

$$B_f \frac{v_f^2}{2g} = \frac{\Delta P}{\rho}$$

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and using $\rho = 49.5 \text{ lb/ft}^3$ and maximum $V_f = 14.3 \text{ ft/sec}$ the following values are obtained for B_f .

Δp (psi)	B_f
17.5	16.0
19.0	17.4
20.5	18.8

The loss due to enlargement of the orifice tube is expressible as

$$B_e = \left(1 - \frac{d_e^2}{d_t^2}\right)^2 = 0.44.$$

The turning loss is assumed to be one velocity head, so that $B_b = 1.0$. The exit loss from the orifice into the outlet plenum is also assumed to be one velocity head, so that $B_o = 1.0$.

Orifice flow is generally expressed in terms of a discharge coefficient, C , which takes into account frictional losses and contraction of the jet. This coefficient is defined by

$$C = \frac{C_v C_c}{\left(1 - \frac{C_c^2 A^2}{A_t^2}\right)^{1/2}}$$

where C_v is the velocity coefficient

C_c is the contraction coefficient

A is the orifice area

A_t is the orifice inlet tube area.

This can be rewritten in terms of the head loss coefficient as follows,

$$B_v = \left(\frac{1}{C_v^2} - 1\right) \left(1 - \frac{C_c^2 A^2}{A_t^2}\right) \quad (10)$$

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which is plotted in Figure 4. We note that B_v does not depend strongly on C_c nor on the ratio of the areas. The required area ratio will probably not exceed $1/4$. The most likely range for C_v is between 0.90 and 0.95. Therefore B_v should range between 0.10 and 0.25.

B. Leakage Flow

All of the coolant will not flow through the orifice as some will be by-passed, leaking through the annulus between the process channel and the orifice extension tube. The head loss relationship for this flow path can be expressed by

$$h_2 = B_f \frac{V_f^2}{2g} + B_L \frac{V_L^2}{2g} \quad (11)$$

The head loss for the parallel paths must be equal so that

$$h_1 = h_2 \quad (12)$$

The results of an analysis of leakage flow through the annulus between the process channel and the orifice extension tube are shown in Figure 5. When the orifice is in the closed position the pressure drop across it and also across the leakage annulus will be about 20 psi. The leakage at 20 psi for several annulus thicknesses is seen to be as follows, for "drawn tubing."

<u>Annulus Thickness</u> <u>(inches)</u>	<u>Leakage at 20 psi</u> <u>lb/sec</u>
1/16	13.4
1/32 *	4.2
1/64	1.3

The annulus thickness should not be greater than $1/32$ of an inch because the required total coolant flow with the orifice in the closed position is only 9.9 lb/sec. The head loss coefficient for a $1/32$ inch thick annulus, one foot long is

$$B_L = f \frac{L}{2a} = 4.8$$

* For "commercial steel" the leakage is 2.7 lb/sec at 20 psi for a $1/32$ " annulus. $B_L = 11.5$ for this case.

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V. Design of Orifice

The division of the flow between the two parallel paths is obtained from equation (12) by substituting the above values for head loss coefficients into equations (9) and (11) and making use of the continuity relationships $V = \frac{W}{A_f}$ and

$$W = W_o + W_l \quad (13)$$

where W = total flow

W_o = flow through orifice

W_l = leakage through annulus.

The following relationship is obtained for a 1/32 inch annulus and is plotted in Figure 6

$$\frac{W_o}{W} = \frac{F}{F + \sqrt{64 + \frac{1 + B_l}{A_o^2}}} \quad (14)$$

$F = 718$ for "drawn tubing" and 1113 for "commercial steel."

The following values were used for the areas, $A_f = 7.51 \text{ in.}^2$,

$A_e = 13.36 \text{ in.}^2$, $A_t = 39.85 \text{ in.}^2$ and $A_l = 0.440 \text{ in.}^2$.

The required orifice area is obtained by substituting the values of the head loss coefficients into equation (9) and making use of the continuity relationships, as follows.

$$h_1 = \frac{W^2}{2g\rho} \left[368 B_f + \left(64 + \frac{1 + B_l}{A_o^2} \right) \frac{W_o^2}{W^2} \right] \quad (15)$$

For the specified core pressure loss of 21 psi this further reduces to

$$\frac{2,650,000}{W^2} = 368 B_f + \left(64 + \frac{1 + B_l}{A_o^2} \right) \frac{W_o^2}{W^2}$$

This equation is solved for A_o , with $B_f = 16.0$, $B_l = 0.1$ and the values of $\frac{W_o}{W}$, which is a function of A_o , obtained

from Figure 6. The required orifice area A , is related to the area of the contracted jet A_o by

$$A_o = C_c A$$

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C_c has been assumed to be 0.60 for the results plotted in Figure 7. The calculations were repeated for $B_f = 17.4$ to show effect of changes in fuel channel pressure loss. This is also shown in Figure 7. Changes in B_f and B_v within the required limits do not exert a strong influence on the orifice area.

The orifice profile for a slot 1.00 inch wide is shown in Figure 8 for a contraction coefficient of 0.60. The actual contraction coefficient must be determined experimentally.

TEMPERATURE SENSITIVITY AS A FUNCTION OF RANGE IN FLOW RATE

$$S = \frac{\Delta T_o}{T_o} \cdot K = \frac{1}{T_o - T_c} \cdot \frac{\Delta T_o}{\Delta Q}$$

W_o = Flow rate with orifice open

W_c = Flow rate with orifice closed

N = Number of orifice adjustment increments

RATIO OF RANGE IN FLOW RATE

FIG. 1

COOLANT FLOW RATE FOR
CONSTANT TEMPERATURE
SENSITIVITY (K/D BY 1000)

$\dot{M} = 3.18$
 $\dot{W} =$

$W = 99.8$ 0.014559

FLOW RATE, $\dot{M}$, lb/sec

FIG. 2

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DATE: <u>10-1-54</u>	<u>FUEL CHANNEL OUTLET</u>	MODEL NO. _____

ORIFICE HEAD LOSS COEFFICIENT

CURVE	C_v	C_d
A	0.95	0.8
B	0.95	0.7
C	0.95	0.6
D	0.90	0.6
E	0.85	0.5

$$K_f \left(\frac{1}{C_v^2} - 1 \right) \left(1 - \frac{C_d^2}{C_v^2} \right)$$

HEAD LOSS COEFFICIENT, K_f

ORIFICE AREA A
INLET TUBE AREA A_t

FIG. 2

LEAKAGE OF COOLANT FROM CALANDRIA BETWEEN PROCESS CHANNEL AND DRIFTE EXTENSION TUBE

DIMENSIONS ARE FOR THICKNESS OF NOMINAL

FIG. 5

FIG. 6

REQUIRED ORIFICE AREA

$\Delta P = 17.5 \text{ psi}$, $C_c = 0.6$

$B_f = 16.0$, $B_v = 0.1$

DRAWN TUBING

$$\frac{965 \times 10^4}{W^2} = 368 B_f + (64 + \frac{1+B_v}{A_o^2}) \frac{W_o^2}{W^2}$$

$$A = \frac{A_o}{C_c}$$

ORIFICE AREA
 $\Delta P = 19.0 \text{ psi}$, $C_c = 0.6$
 $B_f = 12.4$, $B_v = 0.1$
DRAWN TUBING

ORIFICE AREA, A , in^2

8
7
6
5
4
3
2

TOTAL FLOW, W , lb/min

ORIFICE AREA

ORIFICE AREA
 $\Delta P = 17.5 \text{ psi}$, $C_c = 0.6$
 $B_f = 16.0$, $B_v = 0.1$
COMMERCIAL STEEL

FLOW RATE, W , lb/min

40
30
20
10

0 10 20 30 40 50 60 70 80 90

ORIFICE POSITION, θ , degrees

FIG-7

FIG. 10

ORIFICE PROFILE
FOR 1" SLOT

$1AP = 14.5$, $C_d = 0.6$
 $1B_1 = 16.0$, $B_1 = 0.1$
(DRAWN TO SCALE)

ORIFICE HEIGHT

ORIFICE POSITION