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SUBJECT: A Method for Determining the Optimum Dimensional Parameters of a Scalloped Channel so as to Minimize Fuel-Element Bowing in a Septafoil Arrangement

TO: Distribution

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ABSTRACT

The use of a scalloped cross-sectional coolant channel has been suggested as a possible solution of the fuel-element bowing problem inherent in the septafoil type of geometry. Using simplified assumptions, a method has been developed for calculating the rod spacing and scallop size necessary to produce equal average fuel-element surface temperatures in the central and peripheral regions of the coolant flow channel at the mid-section of each fuel-rod cluster under a given set of reactor flow conditions. Since the extent of rod-bowing is related to the surface temperature distribution, this requirement should minimize fuel-element deflection.

DISCLAIMER

NOMENCLATURE

a heated surface area

A cross-sectional flow area

A^* total cross-sectional flow area divided by the total cross-sectional area of fuel elements

c_p fluid specific heat

C length of the rod cluster from the upstream end to the axial position where the average surface temperatures of the outer and inner flow regions are equal

d fuel element diameter

D_e equivalent hydraulic diameter, $4A/P$

D_e^* total equivalent hydraulic diameter divided by the fuel element diameter

f Blasius friction factor defined by $\Delta p = f \frac{L}{D_e} \frac{\rho \bar{u}^2}{2g_c}$

g_c gravitational conversion factor

h film coefficient of heat transfer

k fluid thermal conductivity

L total length of each fuel-element cluster

N dimensionless ratio, $\frac{h_t a_t}{w_t c_p} = \frac{\delta t_t}{\Delta t_t}$

N^* value of $\frac{h_t a_{t,\ell}}{w_t c_p}$ that must exist in order that the average surface temperatures of the outer and inner flow regions be equal at the mid-section of each fuel-element cluster

N_{Re} Reynolds modulus, $\frac{D_e u \rho}{\mu}$ or $\frac{D_e w}{\mu A}$

P flow "wetted" perimeter

P^* total flow wetted perimeter divided by the total heated (fuel-element) perimeter

NOMENCLATURE (Continued)

q	heat-transfer rate
R	radius of scallop
S	center-to-center spacing of fuel elements
$\bar{u}$	mean fluid velocity
w	mass flow rate
Δp	channel pressure drop
δt	fluid temperature rise along the fuel element
Δt	surface-to-fluid temperature difference
μ	fluid dynamic viscosity
ρ	fluid density

Subscripts

c	refers to the length C
i	refers to the inner flow region
ℓ	refers to the total fuel-element cluster length, L
o	refers to the outer flow region
t	refers to the total flow channel

Superscripts

$+$	dimensionless ratio of the outer flow region to the inner flow region; e.g., $\bar{u}^{+} = \bar{u}_o/\bar{u}_i$
$++$	dimensionless ratio of a linear dimension to the fuel-element diameter; e.g., $S^{++} = S/d$

INTRODUCTION

The nonuniform circumferential surface temperature structure existing with the septafoil fuel-element arrangement of the GCR-2 (evidenced in both analytical calculations and experimental studies) leads to axial bowing of the fuel rods. Two major possibilities for alleviating this bowing problem are: (1) switching from the septafoil geometry to some other configuration; or (2) modifying the septafoil (including the flow channel) in such a way as to eliminate, or at least to decrease, the surface temperature maldistribution. Since the septafoil cluster is easily fabricated and has the high surface-to-volume ratio necessary for efficient heat transfer, it was decided that the initial effort should be in the direction of developing a suitable modification of this system.

Epel and Furgerson[1] have suggested that the surface temperature distribution of a septafoil fuel-element cluster might be improved if the flow channel were to have a scalloped cross section. This configuration was conceived by envisioning the seven elements, each surrounded by an annular flow channel, arrayed in an equilateral triangular lattice which was collapsed sufficiently to cause overlap of the individual channels at the points of closest approach of the tubes.

By dividing the coolant channel into an outer flow region and an inner flow region, it is possible (under a set of simplifying assumptions) to determine analytically the axial position along the fuel-element cluster at which the fuel element average surface temperatures in the two regions are

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[1]L. G. Epel and W. T. Furgerson, Temperature Structure in Gas Cooled Reactor Fuel Elements and Coolant Channel, ORNL CF 58-5-97 (May 27, 1958).

equal. Specifically, for any particular flow condition, the rod spacing and scallop size can be chosen to give equal average fuel-element surface temperatures in the two flow regions at the geometrical mid-plane of the fuel-element cluster. It was the purpose of this study to develop such optimum dimensional criteria.

ANALYSIS

The geometry under consideration is given in Fig. 1. In this, the inner and outer flow regions are to be considered as physically separated by the centerlines joining the peripheral fuel elements. In the analysis the subscript i refers to the inner flow region, the subscript o, to the outer region, and the subscript t, to the total flow channel. The superscript + defines the dimensionless ratio of any quantity for the outer region to the same quantity for the inner region; e.g., $\bar{u}^{+} = \bar{u}_o/\bar{u}_i$. The subscript ℓ is used to denote the entire fuel-element cluster, while the subscript c indicates the region from the fuel-element cluster inlet end to the axial position at which the inner and outer average fuel-element surface temperatures are equal. Without the subscripts c or ℓ, a quantity refers to the region from the inlet to any arbitrary axial position along the cluster.

The analysis was performed under the following set of assumptions:

(a) The inner and outer flow regions are hydrodynamically and thermally isolated.

(b) The inner and outer flow regions have the same length:

$$L^{+} = 1 \ . \tag{1}$$

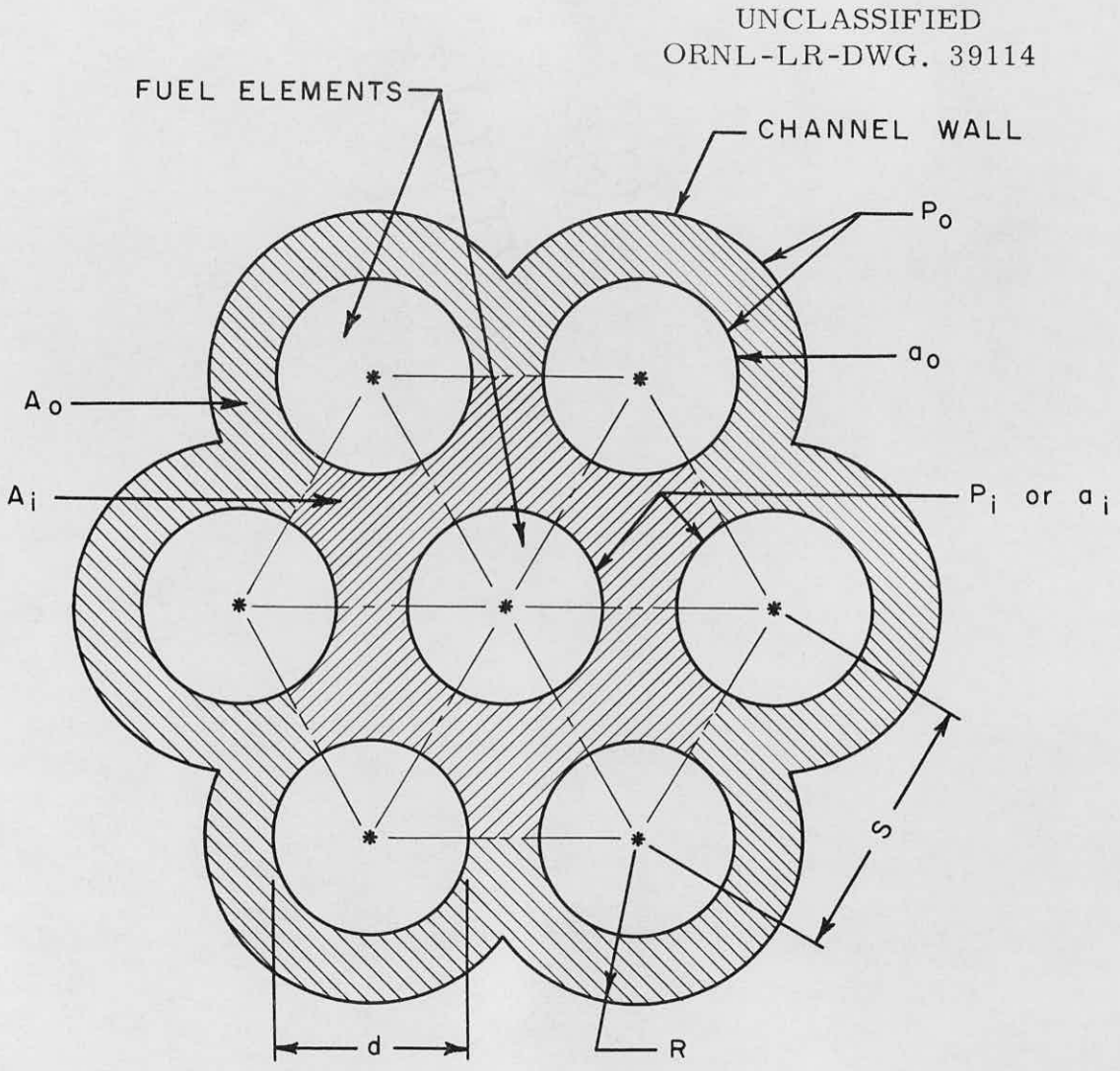

Fig. 1. A Scalloped Cross-Sectional Coolant Channel Containing Septafoil Fuel Elements.

(c) The pressure drop through each region is the same:

$$\Delta p^+ = 1 \ . \tag{2}$$

(d) The fluid physical properties in each region are the same:

$$\rho^+ = 1, \ k^+ = 1, \ \mu^+ = 1, \text{ and } c_p^+ = 1 \ . \tag{3}$$

(e) Uniform heat transfer exists around the fuel-element surface:

$$(q/a)^+ = 1 \ . \tag{4}$$

(f) Fully turbulent flow exists along the entire length of the flow channel.

(g) The fluid friction in both flow regions is given by the same relation:

$$f^+ = \left(N_{Re}^+\right)^{-0.2} \ . \tag{5}$$

(h) The heat transfer in each of the flow regions is described by the same law:

$$h^+ \ D_e^+ = \left(N_{Re}^+\right)^{0.8} \ , \tag{6}$$

(the property relations are eliminated by Eq. 3).

(i) The inlet fluid temperature is the same for both the inner and outer flow regions.

The following hydrodynamic and thermodynamic equations relating the two regions can then be written in terms of the dimensionless parameters defined:

Pressure Drop

By definition of the Blasius friction factor,

$$\Delta p^+ = f^+ \ \frac{L^+}{D_e^+} \ \rho^+ \ (\bar{u}^+)^2 \ .$$

Combining this with Eqs. 1, 2, and 3, there results

$$f^+ (\bar{u}^+)^2 / D_e^+ = 1 ,$$

which on substitution into Eq. 5 yields,

$$\left(N_{Re}^+\right)^{-0.2} (\bar{u}^+)^2 / D_e^+ = 1 .$$

By definition,

$$N_{Re}^+ = \frac{D_e^+ \bar{u}^+ \rho^+}{\mu^+} = D_e^+ \bar{u}^+ .$$

Then, eliminating $\bar{u}^+$ between these two equations and solving for the Reynolds modulus ratio, there is obtained

$$N_{Re}^+ = \left(D_e^+\right)^{5/3} . \qquad (7)$$

Heat Transfer

By definition of the heat-transfer coefficient,

$$(q/a)^+ = h^+ \Delta t^+$$

or substituting from Eq. 4,

$$h^+ \Delta t^+ = 1 .$$

Combining this with Eq. 6,

$$\left(N_{Re}^+\right)^{0.8} \Delta t^+ / D_e^+ = 1 .$$

Eliminating the Reynolds modulus ratio between this equation and Eq. 7, results in

$$\left(D_e^+\right)^{1/3} \Delta t^+ = 1 . \qquad (8)$$

Geometry

The ratio of the heated surface of the outer region to that of the inner region (see Fig. 1) is 4:3 or

$$a^+ = 4/3 \ . \tag{9}$$

Mass Flow Rate

From the definition of the Reynolds modulus and Eq. 3,

$$N_{Re}^+ = D_e^+ \, w^+ / A^+ \ .$$

Eliminating N_{Re}^+ between the above equation and Eq. 7, there results

$$w^+ = A^+ \left(D_e^+ \right)^{2/3} \ . \tag{10}$$

Conservation of Energy

The convection heat gain (invoking Eq. 3) is given by

$$q^+ = w^+ \, \delta t^+ \ .$$

Combining this with Eqs. 4 and 9 yields

$$w^+ \, \delta t^+ = 4/3 \ .$$

Then, eliminating w^+ between this equation and Eq. 10,

$$A^+ \left(D_e^+ \right)^{2/3} \delta t^+ = 4/3 \ . \tag{11}$$

Considering the entire flow channel, the total mean fluid temperature rise can be written as

$$\delta t_t = \frac{w_i \, \delta t_i + w_o \, \delta t_o}{w_i + w_o} = \frac{\delta t_i + w^+ \, \delta t_o}{1 + w^+} \ . \tag{12}$$

Further, the average (total) mean surface-to-fluid temperature difference

is defined by the expression:

$$\Delta t_t = \frac{a_i \, \Delta t_i + a_o \, \Delta t_o}{a_i + a_o} = \frac{3\Delta t_i + 4\Delta t_o}{7} \quad , \tag{13}$$

since $a^+ = a_o/a_i = 4/3$ (and $L^+ = 1$).

From $q_t = w_t \, c_p \, \delta t_t = h_t \, a_t \, \Delta t_t$, a dimensionless ratio can be defined as

$$N = \frac{h_t \, a_t}{w_t \, c_p} = \frac{\delta t_t}{\Delta t_t} \, . \tag{14}$$

This parameter varies directly with cluster length from zero at the inlet to its maximum value at the outlet. Thus for the total fuel-element cluster,

$$N_\ell = \frac{h_t \, a_{t,\ell}}{w_t \, c_p} = \frac{h_t \, L \, 7\pi d}{w_t \, c_p} \tag{15}$$

and for the axial position at which the average fuel-element surface temperatures are the same for both the outer and inner flow regions

$$N_c = \frac{h_t \, a_{t,c}}{w_t \, c_p} = \frac{h_t \, C \, 7\pi d}{w_t \, c_p} \tag{16}$$

and from these equations

$$\frac{N_\ell}{N_c} = \frac{L}{C} \, . \tag{17}$$

Under the assumption that the fluid temperature is constant at the inlet to the fuel-element cluster, the average surface temperatures of the outer and inner flow regions will be the same only at the axial position where

$$\Delta t_o + \delta t_o = \Delta t_i + \delta t_i \, . \tag{18}$$

The parameter N_c can be expressed in terms of D_e^+ and A^+ to satisfy the conditions of Eq. 18 by combining Eqs. 8, 10 through 14, and 18. N_c is then obtained as:

$$N_c = \frac{49 \left(D_e^+\right)^{2/3} A^+ \left[\left(D_e^+\right)^{1/3} - 1 \right]}{\left[4 + 3 \left(D_e^+\right)^{1/3}\right] \left[4 - 3 \left(D_e^+\right)^{2/3} A^+\right] \left[\left(D_e^+\right)^{2/3} A^+ + 1 \right]} . \qquad (19)$$

A quantity N^* can now be defined which is the value of N_ℓ for which equal average surface temperatures will occur at the mid-section of the cluster. Since this corresponds to the position, $C = \frac{L}{2}$, Eq. 17 yields the result

$$N^* = 2 N_c .$$

Combining this with Eq. 19 gives

$$N^* = \frac{98 \left(D_e^+\right)^{2/3} A^+ \left[\left(D_e^+\right)^{1/3} - 1 \right]}{\left[4 + 3 \left(D_e^+\right)^{1/3}\right] \left[4 - 3 \left(D_e^+\right)^{2/3} A^+\right] \left[\left(D_e^+\right)^{2/3} A^+ + 1 \right]} . \qquad (20)$$

If at Eq. 13 a mean h rather than a mean Δt is defined, Eq. 20 is obtained in the alternate form:

$$(N^*)' = \frac{2 \left(D_e^+\right)^{1/3} A^+ \left[\left(D_e^+\right)^{1/3} - 1 \right] \left[3 + 4 \left(D_e^+\right)^{1/3}\right]}{\left[1 + A^+ \left(D_e^+\right)^{2/3}\right] \left[4 - 3 A^+ \left(D_e^+\right)^{2/3}\right]} . \qquad (20')$$

Then, forming the ratio of Eq. 20 to Eq. 20':

$$\frac{N^*}{(N^*)'} = \frac{49 \left(D_e^+\right)^{1/3}}{\left[4 + 3 \left(D_e^+\right)^{1/3}\right] \left[3 + 4 \left(D_e^+\right)^{1/3}\right]} .$$

For $D_e^+ = 1$, this reduces to $N^* = (N^*)'$. Since in this derivation h and Δt are known only as the product $h\Delta t$, it is to be expected that independent definitions of the mean values of h and Δt will, in general, yield the result that $N^* \neq (N^*)'$. This follows from the generalization that the product of the means of two functions is not equal to the mean of their product. As can be shown from equations obtained later in the analysis, $\left(D_e^+\right)_{min} = 0.5944$. Substituting this value into the above equation yields the result that $N^*/(N^*)' = 0.993$, or a variation of less than 1% is introduced by the alternate derivation.

For the configuration under consideration (see Fig. 1), providing $R^{++} \geq S^{++}/2$ (i.e., adjacent scallops intersect or are tangent), it can be shown that

$$A^+ = \frac{\frac{S^{++} R^{++}}{2} \sin\left(\arccos \frac{S^{++}}{2 R^{++}}\right) + (R^{++})^2 \left(\frac{2\pi}{3} - \arccos \frac{S^{++}}{2 R^{++}}\right) - \frac{\pi}{6}}{\frac{\sqrt{3}}{4} (S^{++})^2 - \frac{\pi}{8}} \tag{21}$$

and

$$P^+ = \frac{\frac{2\pi}{3} + 2 R^{++} \left(\frac{2\pi}{3} - \arccos \frac{S^{++}}{2 R^{++}}\right)}{\frac{\pi}{2}} \tag{22}$$

where R^{++} is the ratio of the radius of the scallop, R, to the tube diameter, d, and S^{++} the similar ratio of the fuel element center-to-center distance, S, to the tube diameter.

Since

$$D_e^+ = A^+/P^+ , \tag{23}$$

it is possible to express N^* in terms of S^{++} and R^{++}.

To provide convenient comparison of different dimensional configurations, a number of additional dimensionless parameters can be defined:

$$A^* = \frac{\text{total cross-sectional flow area}}{\text{total cross-sectional area of fuel elements}} \tag{24}$$

$$= \frac{A_t}{\frac{7}{4}\pi d^2} = \frac{3}{7}\left[\frac{2\sqrt{3}}{\pi}\left(S^{++}\right)^2 - 1\right](1 + A^+) ,$$

$$P^* = \frac{\text{total flow wetted perimeter}}{\text{total heated (fuel-element) perimeter}} \tag{25}$$

$$= \frac{P_t}{7\pi d} = \frac{3}{7}(1 + P^+) ,$$

$$D_e^* = \frac{\text{total equivalent hydraulic diameter}}{\text{fuel-element diameter}} \tag{26}$$

$$= \frac{D_{e_t}}{d} = \left[\frac{2\sqrt{3}}{\pi}\left(S^{++}\right)^2 - 1\right]\left(\frac{1 + A^+}{1 + P^+}\right) = \frac{A^*}{P^*} .$$

NUMERICAL RESULTS

The parameters N^*, A^*, P^*, and D_e^* have been calculated for $S^{++} = 1.2$, 1.4, and 1.6 in the respective ranges of R^{++} that yield a positive value for N^*; i.e., N^* between 0 and $+\infty$. These limits are given in Table 1.

Table 1. Limits of R^{++} for Given Values of S^{++}

S^{++}	N^*	R^{++}
1.2	∞	0.680
1.2	0	0.781
1.4	∞	0.828
1.4	0	1.036
1.6	∞	0.981
1.6	0	1.321

The results are plotted in Figs. 2 and 3.

DISCUSSION

The foregoing analysis, although greatly simplified, provides much insight into the surface temperature structure of this type of reactor core geometry.

If the flow channel is designed to fulfill the requirements of Eq. 20, the average surface temperatures of the outer and inner flow regions will be the same at the mid-section of the fuel-element cluster. This will produce minimum rod bowing (as illustrated in Fig. 4). For the scalloped channel satisfying Eq. 20, it can be shown that the outer flow region will

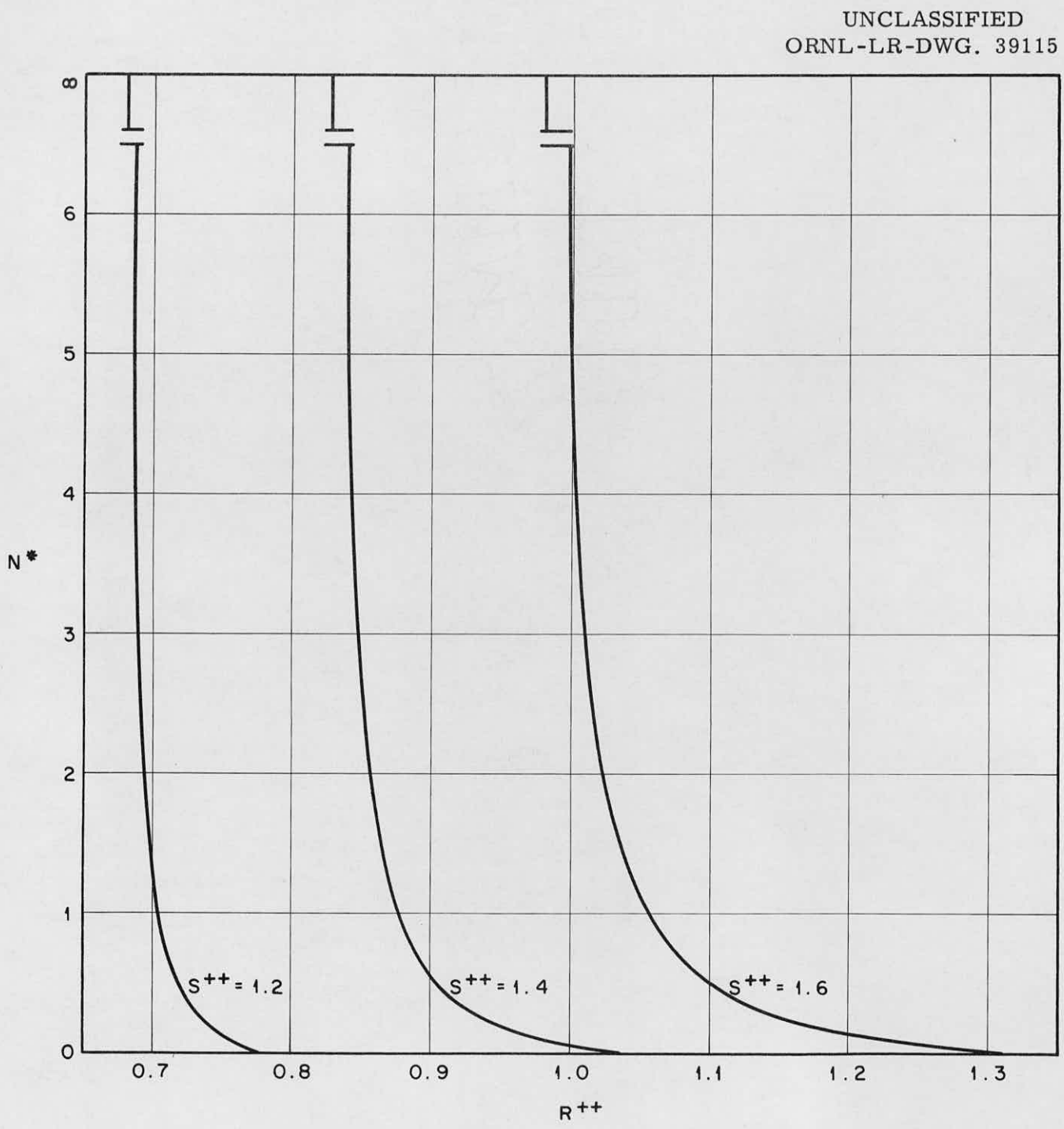

Fig. 2. N^* as a Function of R^{++} for $S^{++} = 1.2, 1.4$ and 1.6.

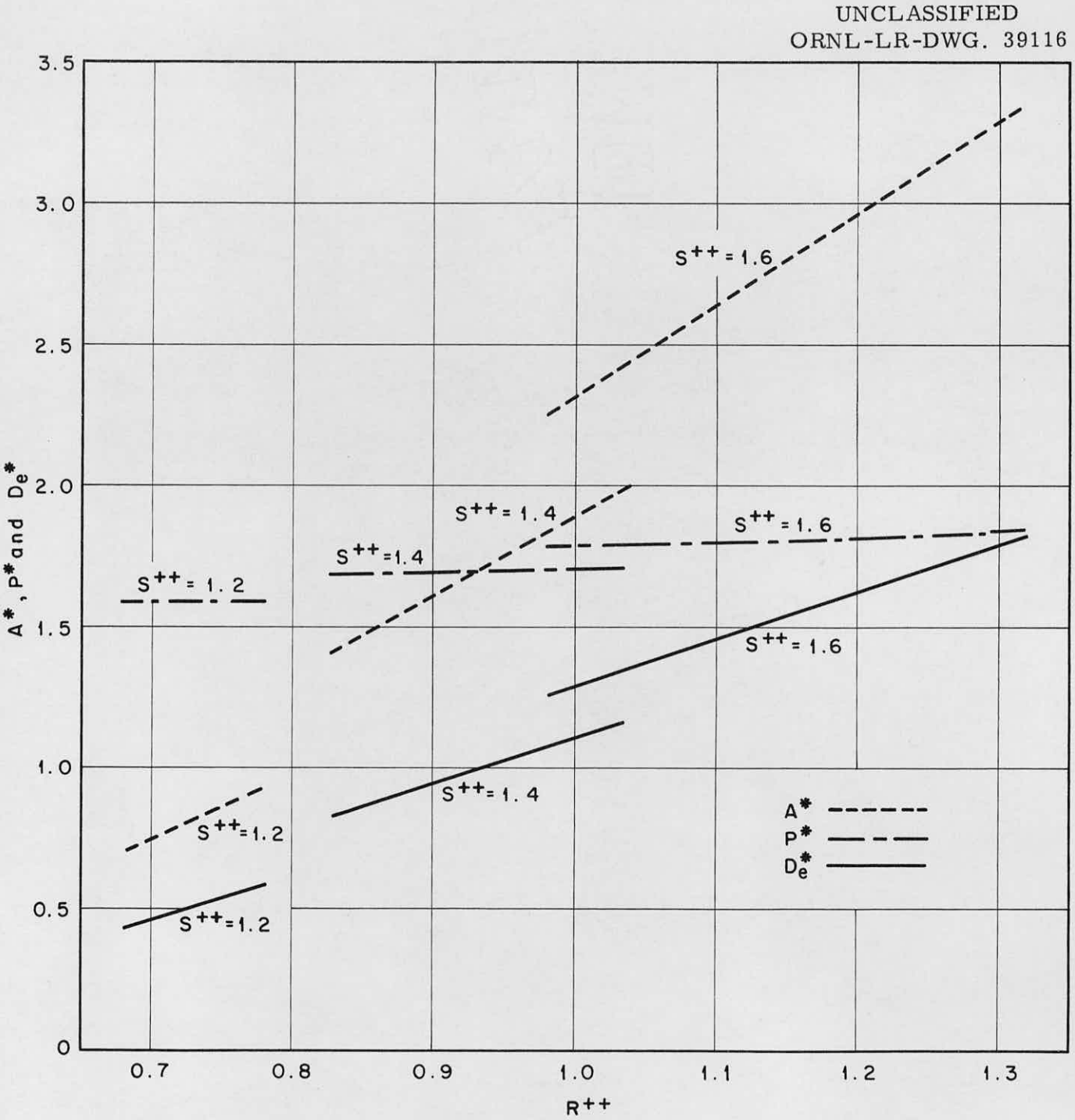

Fig. 3. A^*, P^* and D_e^* as a Function of R^{++} for $S^{++} = 1.2, 1.4$ and 1.6.

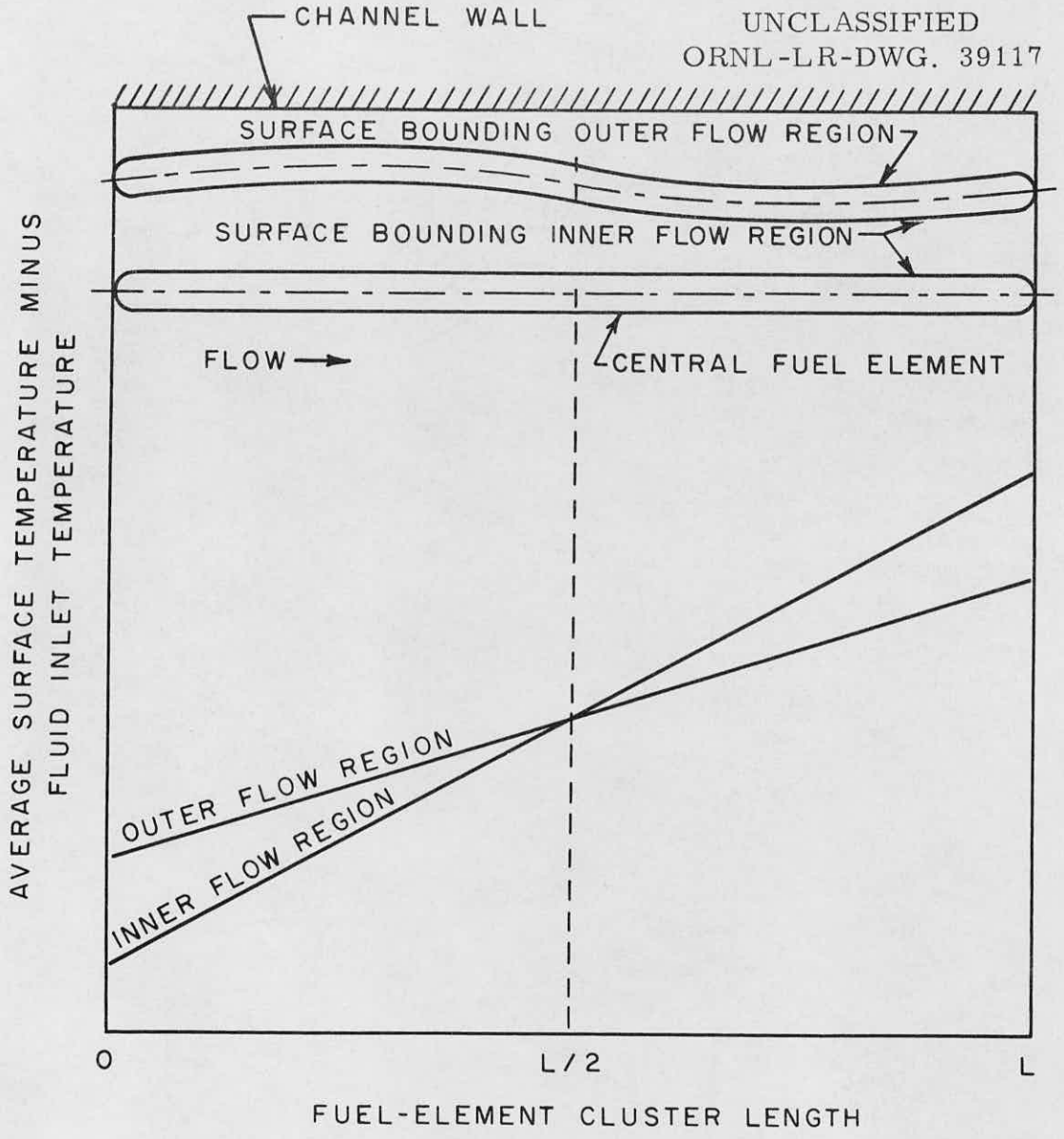

Fig. 4. Fuel Element Surface Temperature and Deflection for Minimum Bowing.

have a higher surface temperature than that of the inner flow region at the inlet to the cluster; hence, the direction of bowing will be as is shown in Fig. 4.

The ideal condition would be one in which the surface temperatures of both flow regions are the same for any axial position along the cluster; i.e., $\delta t_o = \delta t_i$ ($\delta t^+ = 1$), and $\Delta t_o = \Delta t_i$ ($\Delta t^+ = 1$). In general, however, δt^+ and Δt^+ will not be both equal to unity. This can be illustrated by considering Eq. 20 for the two conditions $\Delta t^+ = 1$ and $\delta t^+ = 1$. If we choose $\Delta t^+ = 1$, then Eq. 8 yields $D_e^+ = 1$ and Eq. 20 gives the result $N^* = 0$ (it can be shown that the denominator of Eq. 20 cannot be zero for this case[2]). On the other hand, if we choose $\delta t^+ = 1$, substitution into Eq. 11 yields $D_e^+ = \left[4/(3\ A^+)\right]^{3/2}$. Then, evaluation of Eq. 20 gives the result $N^* \to +\infty$. In this case, since $A^+ > 4/3$, it is seen that D_e^+ cannot have the value 1. Thus, it is not possible with this geometry to obtain correspondence of the surface temperatures in the inner and outer regions over the entire length of the tube. As an approximation, however, to this ideal temperature structure, the conditions of Eq. 18 can be satisfied for a single position along the tube, say at the mid-plane of the fuel-element cluster. From Fig. 4, it is apparent that matching the surface temperatures at the longitudinal center of the element yields minimum values of the inner-outer surface temperature differences and hence minimum bowing.

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[2]For the denominator to be zero, it is necessary that $A^+ = 4/3$. By definition, $A^+ = D_e^+ P^+$ or $A^+ = P^+$. Then, $P^+ = P_o/P_i = (P_s + P_o')/P_i$, where P_s is the perimeter of the channel wall and $P_o' = a_o/L$. Further as $a = PL$, $P^+ = (P_s/P_i) + a^+ = (P_s/P_i) + (4/3)$. Since $P_s/P_i > 0$, $A^+ > 4/3$; and hence the denominator in Eq. 20 is not zero.

To illustrate the use of this analysis, the desired value of N_ℓ will generally be known for a given design. For minimum bowing, $N_\ell = N^*$ (from Eq. 17, using $N^* = 2\ N_c$ and $C = L/2$). Then, the values of S^{++} and R^{++} associated with this N^* can be obtained from Fig. 2. Finally, Fig. 3 can be used to establish the relative values of A, P, and D_e. These values (in conjunction with such restrictions as may be placed by the mass flow rate, allowable pressure drop, nuclear considerations, etc.) enable the selection of a fuel-element cluster and flow channel design that will be the best compromise between rod bowing and other desirable objectives. The solution of this system requires application of an iterative technique. For practical design work, of course, complete families of these curves would be desirable.

By way of example, consider a reactor having 1-in.-dia fuel rods spaced on 1.4-in. centers ($S^{++} = 1.4$) located within a channel through which gas is flowing at the rate of 3,000 lb_m/hr. The gas is assumed to have the following properties: $\mu = 0.09\ lb_m/hr \cdot ft$, $k = 0.16$ Btu/hr·ft·°F, $c_p = 1.2$ Btu/lb_m·°F, and $N_{Pr} = 0.7$. Using the correlation,

$$N_{Nu} = 0.023\ N_{Re}^{0.8}\ N_{Pr}^{0.4} \tag{27}$$

(where N_{Nu} is the Nusslet modulus and N_{Pr} is the Prandtl modulus) the optimum rod cluster length can be determined for values of R^{++} of 0.9 and 1.0. Thus, for $R^{++} = 0.9$, Fig. 2 yields $N^* = 0.55$ and Fig. 3 gives $A^* = 1.61$, $P^* = 1.70$, and $D_e^* = 0.95$. Then, $P_t = P^*\ \pi d$ or 3.12 ft and $D_{e_t} = D_e^*\ d$ or 0.079 ft. The Reynolds modulus is then calculated as,

$$N_{Re} = \frac{4\ w_t}{P_t\ \mu} = 42{,}700\ ,$$

and from Eq. 27, h_t is 204 Btu/hr·ft^2·°F. Since $L = \frac{N^* w_t c_p}{h_t 7\pi d}$, the optimum cluster length is found to be 5.3 ft. Similarly, for $R^{++} = 1.0$, $N^* = 0.19$ and $A^* = 1.90$, $P^* = 1.71$ and $D_e^* = 1.11$. By the same procedure, the optimum cluster length is determined to be 2.1 ft. Thus, relatively small changes in channel parameters (18% for A^*, < 1% for P^*, and 17% for D_e^*) result in a reduction of the optimum cluster length by a factor of 2.5. If other criteria establish the desired rod cluster length, an iterative technique can be used to determine the optimum channel parameters for the chosen cluster length.

In this analysis, a number of simplifications have been made to facilitate the solution. For instance, the inlet fluid temperature to each cluster was assumed to be uniform across the entire flow channel. This presupposes complete mixing of the coolant as it passes through the hanger-spacer assembly between clusters. The relative validity of this assumption is unknown, and it is difficult to ascertain how it could be verified without resorting to an elaborate experimental program.

In discussing the temperature profile produced in a scalloped channel, the rather tacit assumption was made that the average and maximum surface temperatures for either flow region were the same or very closely allied. For the geometry of the scalloped channel, this assumption is not unreasonable. Prior analytical work[3] and experimental work[4] show that for the inner flow region of a similar configuration, the temperature profile is almost uniform causing the average and maximum temperatures to coincide fairly well.

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[3] Op. cit.

[4] Gas-Cooled Reactor Project Semiannual Progress Report for Period Ending December 31, 1958, ORNL-2676, pp 36-45.

Since the outer flow region is essentially annular in cross section, there should be no great difference between the maximum and average temperatures.

As a matter of simplification, and in lieu of better information, the heat generation in and the thermal properties of the fuel elements were considered to be uniform.

The analysis could be made more exact by eliminating some of these simplifying assumptions and by dividing the flow channel into a greater number of flow regions and applying the proper variations in the thermal properties, heat-transfer coefficients, etc., to each region. Also, as the peripheral fuel rods begin to bow, the flow distribution between adjacent flow regions will be changed. Since these secondary effects can be cumulative, they should be included in any detailed analysis. Since, in any event, the results obtained will require experimental verification, it is believed that such refinements are not now justified.

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