MAY 26 1960

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A Division of North American Aviation, Inc.

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WRITTEN BY H. Jackel		ATOMICS INTERNATIONAL A Division of North American Aviation, Inc.	TDR NO.	
SECTION	Sodium Reactors		5011	
GROUP	Engineering		GO 7519	
UNIT	Reactor Technology		LEDGER ACCT. 3621	
APPROVED BY: (SUPERVISOR) <i>WPC</i>		PROGRAM	SUB-ACCT. 4410	
OTHER		Sodium Cooled Fast Reactor	TWR	
		PROJECT	DATE February 24, 1960	
		Advanced Sodium Reactors	PAGE 1 OF 18	

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SUBJECT: A Preliminary Nuclear Analysis of a Sodium Cooled Fast Reactor (SCFR)
With UC Fuel Elements in a Skewed Hexagonal Array

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I STATEMENT OF PROBLEM

To perform a nuclear analysis on a sodium-cooled, enriched-uranium-carbide fueled fast reactor core of unique design with fuel elements skewed, varying the lattice over the length of the core. In particular, to determine the ratio of peak to average power density, and to evaluate blanket and reflector designs.

II SUMMARY OF RESULTS AND RECOMMENDATIONS

The core, in its final form, consists of 199 stainless steel process tubes, 5.00 in. OD x 0.0625 in. wall, in fixed skewed positions between fixed grid-plates and in a triangular array. Extensions of these tubes pass thru to the top of the biological shield to facilitate the refueling procedure. The overall core dimensions are listed in Table I.

TABLE I
Approximate Dimensions and Description of The Final SCFR Core

Height of fueled region	7 ft.
Thickness of axial blankets	18 in.
Diameter of fueled region	46 in.*
Thickness of radial blanket	15 in.*
Number of fuel elements	66
Number of control rods	7
Number of blanket elements	126

* Values are volume weighted averages

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II SUMMARY OF RESULTS AND RECOMMENDATIONS (Continued)

The lattice spacing at the top of the shield was set by the shield strength requirements at 11.00 in. and at the mid-plane of the active core at 5.018 in. by nuclear requirements. The distance between these two planes is 25.00 ft, and the lower grid-plate is about 7 ft below the mid-plane. In moving up the core from the lower grid-plate to the top of the biological shield the array of tubes rotates thru 90°, while the lattice spacing first contracts from 5.625 in. to 5.018, and then expands to 11.00 in. Around the array of tubes and centered on the mid-plane is a graphite reflector approximately 18 in. thick and 10 ft in height.

The fuel elements are 10 ft long and contain 61 fuel rods. There is a 7 ft length of enriched UC with a 1.5 ft length of depleted UC on each end. The UC slugs, 0.413 in. diameter, are encased in stainless steel tubes, 0.453 in. OD x 0.010 in. wall, with a 0.010 in. sodium bond between the slugs and the tube wall. The blanket elements, containing depleted UC, are also 10 ft in length but consist of 7 rods 1.50 in. diameter and 6 rods 0.50 in. diameter. The larger rods are stainless steel tubes, 1.500 in. OD x 0.010 in. wall, containing 1.440 in. diameter slugs and a 0.020 in. thick sodium bond. The smaller rods are 0.500 in. OD x 0.010 in. wall tubes, also of stainless steel, with 0.460 in. diameter slugs and a 0.010 in. thick sodium bond.

The results of the nuclear analysis of the final SCFR core are listed in Table II. These results indicate that an enrichment of about 15.5% would be necessary to reach criticality.

TABLE II

Results of the Nuclear Calculations on the Final SCFR Core

Direction of Solution	Radial	Axial
Median Fission Energy (Kev)	200	206
Enrichment(atom percent)	15.3	15.8
Initial Conversion Ratio	1.120	0.652
Initial Conversion Ratio,Including Axial Blanket	1.17	—
Initial Volume Weighted Peak to Average Power Density Ratio	1.566	1.370

This core would contain about 10,000 kg enriched UC and 31,300 kg depleted (less than 0.3 atom percent U-235) UC. The reflector contains about 16,200 kg of graphite.

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II SUMMARY OF RESULTS AND RECOMMENDATIONS (Continued)

Because the value of L/D for this core is quite unfavorable based on considerations of minimum critical mass (it is greater than 1.6) it would probably be desirable to modify the core. Since the heat transfer requirements will not allow a significant reduction in L without a corresponding increase in D , and since the radial blanket is considerably more effective than the axial blanket, it appears that replacing those blanket elements adjacent to fuel elements with fuel elements and adding a sufficient number of blanket elements around the outside to maintain the same blanket thickness would be advantageous. A modification of this nature would probably reduce the enrichment necessary, although the total amount of UC would, of course, be increased. The critical mass would probably increase also. A reduction of L/D could also be obtained by increasing the blanket thickness. This would both decrease the critical mass and increase the conversion ratio. If either or both of these modifications were used it would then be desirable to increase the distance from the core mid-plane to the top of the biological shield so that the angle which the outer process tubes make with the vertical would not become too large and thus present problems in refueling. The concept of a rotatable grid-plate constitutes an effective method of controlling a fast reactor by changing the lattice spacing. Such a method might be used to allow for depletion of the fuel as well as for scrams and normal shutdowns.

III METHOD USED

A. Method

All reactor calculations were made using GNU-II, a multiregion, multigroup one-dimensional neutron diffusion code¹ with 32 group cross sections. All cores were considered to be just critical and clean, that is, without control or fission product poisons present.

After calculation of the actual geometry of a core, it was transformed first into a hyperboloid of revolution, and then into a right circular cylinder of about equal height and volume, and the materials homogenized in this volume. This model was used to obtain the radial solution of the core. For the axial solution of the core, the cylinder was transformed into a rectangular parallelepiped of the same height and volume, and with a square cross section in the plane normal to the direction of the solution. Material densities for the axial solution were the same as for the radial solution, and account for almost all of the masses involved, slight variations being due to the approximations necessary in the height because of the slight variation across the ends of the core. The method and equations used for the transformations in geometry are given in Appendix A. Appendix B gives the equations for calculating the material densities.

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III METHOD USED (Continued)

B. Discussion of the Calculations

The values given as conversion ratio reflect a correction made to the GNU output to account for those absorptions in U-238 which produce fissions. This correction, which is shown in detail in Appendix C, allows the values quoted in Table I to give a more realistic picture of the initial production of new fuel.

The average power density in the core is computed from the power density distribution as printed in the GNU output. The equation used for the radial solution² is:

$$\bar{P} = \frac{(2S-1)P_s + P_0 + 4 \sum_{n=1}^{s-1} nP_n}{2S^2}$$

where

- $\bar{P}$ = Average power density
- P_n = Power density at point n
- n = Mesh point number ($0 \leq n \leq s$)
- P_0 = Power density at the center
- P_s = Power density at the outer boundary
- s = Mesh point number at the outer boundary

For the axial solution, since the cross-sectional area was the same at any elevation, the average power density is equal to the average height of the power density distribution curve. This is easily calculated by using "Simpson's Rule" for the area under a curve.

IV REFERENCES

1. "GNU A Multigroup One-Dimension Diffusion Program for the IBM-704" J. M. Bookston et. al. GMR 101 General Motors Corporation.
2. Personal communication with S. Burton.

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APPENDIX

A. A Method for Transforming a Skewed Element Core Into One of Simpler Geometry

The transformation of the skewed element core into a right circular cylinder, or into a rectangular parallelepiped with square cross-section, having approximately the same height and volume as the actual core can be made using the geometric relationships between any two elements. This transformation is done in two steps. First, the skewed element core, which has a hexagonal cross-section is changed into a hyperboloid of revolution, which has a circular cross-section. The transformation is such that at the same elevation the two figures have the same cross-sectional area. The second step changes the hyperboloid into one or more right circular cylinders having approximately the same total height and volume as the hyperboloid. The geometric relationships derived here are based, for simplicity, upon the central, vertical, element and an element at one of the vertices of a regular hexagon which has the vertical element at its center (See Figure 1).

Figure 2 shows part of the plan view, and the elevation view in which both elements appear in their true lengths. The dimensions shown are defined below:

- P = is any point on a vertex element
- h = vertical distance from the mid-plane of the active core to a horizontal plane passing through point P.
- H = vertical distance from ^{the} mid-plane of the active core to the top of the biological shield
- G_A = limit of h for the active core
- G_R = limit of h for the axial blanket
- L_H = distance along the element from the mid-plane of the active core to the top of the biological shield
- L_A = ½ the active length of a fuel element minus the axial blanket
- L_R = ½ the active length of a fuel element including the axial blanket
- L_R = ½ the active length of a blanket element
- l = the projection of r on the vertical plane containing the vertex element

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Plan View of the Relative Positions of the Two Elements used in the Derivation of the Equations for the Geometric Transformations

FIGURE 1

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The Geometry for a Skewed Element Core, Showing the Center-lines of the Central Element and of a Vertex Element

FIGURE 2

APPENDIX (Continued)

- r = the horizontal distance from the vertical element to point P
- a = the horizontal distance at the mid-plane from the vertical element to the vertex element
- b = the horizontal distance between the two elements at the top of the biological shield
- c = the horizontal projection of that segment of the vertex element between the mid-plane and the top of the biological shield
- s = lattice spacing at any elevation h
- n = the number of hexagonal rings, completed or uncompleted, at elevation h
- n ≥ 0

From the Figure it can be seen that

$$r^2 = a^2 + l^2 \quad (1)$$

$$\frac{l}{d} = \frac{h}{H} \quad (2)$$

$$d^2 = b^2 - a^2 \quad (3)$$

From equation (2) $l^2 = \frac{h^2}{H^2} c^2$ (2a)

Substituting (2a) in (1) $r^2 = a^2 + \frac{h^2}{H^2} c^2$ (4)

Substituting (3) in (4) $r^2 = a^2 + \frac{h^2}{H^2} (b^2 - a^2)$ (5)

It can be shown that: $s = \frac{r}{n}$ (6)

or $s^2 = \frac{r^2}{n^2}$ (6a)

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Also that:

$$a = A n \quad (7) \quad \text{or} \quad a^2 = A^2 n^2 \quad (7a)$$

$$b = B n \quad (8) \quad \text{or} \quad b^2 = B^2 n^2 \quad (8a)$$

$$c = C n \quad (9) \quad \text{or} \quad c^2 = C^2 n^2 \quad (9a)$$

where

A = Minimum lattice spacing

B = Maximum lattice spacing

$$C^2 = B^2 - A^2 \quad (10)$$

Substituting (7a) and (8a) in (5)

$$r^2 = A^2 n^2 + \frac{h^2}{H^2} (B^2 n^2 - A^2 n^2) \quad (11)$$

Substituting (6a) and (10) in (11)

$$s^2 = A^2 + \frac{h^2}{H^2} C^2 \quad (12)$$

If the unit cell is defined as the equilateral triangle formed by three mutually adjacent elements, then the area of the cell A_o is:

$$A_o = \frac{s^2 \sqrt{3}}{4} \quad (13)$$

and the area of the core A_c is:

$$A_c = N_c A_o \quad (14)$$

where N_c = the number of cells having a lattice spacing s.

Substituting (12) and (13) in (14)

$$A_c = N_c \frac{\sqrt{3}}{4} \left(A^2 + \frac{h^2}{H^2} C^2 \right) \quad (15)$$

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where N is now the number of cells at elevation h , or twice the number of elements, and A_c is the cross-sectional area of the core at the same elevation.

This core, of hexagonal cross-section can be transformed into a core with circular cross-section by letting:

$$A_c = \pi R_e^2 \quad (16)$$

or
$$R_e = \left(\frac{A_c}{\pi} \right)^{1/2} \quad (16a)$$

where R_e is the radius at elevation h of a core of equal volume.

Substituting (15) in (16a)

$$R_e = \left[\frac{N_c \sqrt{3}}{4\pi} \left(A^2 + \frac{h^2}{H^2} C^2 \right) \right]^{1/2} \quad (17)$$

The limits on the values of h for the vertex elements, as a function of n is derived as follows:

From Figure 1 it can be seen that:

$$\frac{G_i}{L_i} = \frac{H}{L_H} \quad (18)$$

or
$$G_i = \frac{H}{L_H} L_i \quad (18a)$$

where the subscript i stands for either A, denoting a fuel element, or R, denoting a reflector element, or the blanket portion of a fuel element

Also
$$L_H^2 = H^2 + C^2 \quad (19)$$

or substituting (9a) in (19)
$$L_H = (H^2 + C^2 n^2)^{1/2} \quad (19a)$$

Substituting (19a) in (18a)

$$G_i = \frac{H L_i}{(H^2 + C^2 n^2)^{1/2}} \quad (20)$$

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This equivalent core (a hyperboloid of revolution) or sections of it, may be transformed into a right circular cylinder of the same height and volume. Although the doming effects which occur at the ends have been neglected, they could be taken into consideration by the same, or similar, method as the following:

For the cylindrical model, the volume is:

$$V_M = \pi R_M^2 h_M \quad (21)$$

where V_M , R_M and h_M are the volume, radius and height respectively of the model.

The volume of the hyperboloid core, V_H , is:

$$V_H = \int_h \pi R_e^2 dh \quad (22)$$

or substituting (17) in (22)

$$V_H = \int_h \pi \frac{N_c \sqrt{3}}{4\pi} (A^2 + \frac{h^2}{H^2} C^2) dh \quad (23)$$

or

$$V_H = \frac{2\sqrt{3}}{4} \int_0^{h_{max}} N_c (A^2 + \frac{h^2}{H^2} C^2) dh \quad (23a)$$

By assuming that N_c is a constant and equal to its maximum value we are in effect neglecting the doming at the ends. If we consider N_c as a discontinuous function of h we may take this effect into account. However, neglecting this effect, then:

$$V_H = N_{c_{max}} \frac{2\sqrt{3}}{4} (A^2 + \frac{h_{max}^2}{3H^2} C^2) h_{max} \quad (24)$$

Letting $h_M = 2h_{max}$ and equating (21) and (24)

$$\text{then } R_M^2 = N_{c_{max}} \frac{\sqrt{3}}{4\pi} (A^2 + \frac{h_{max}^2}{3H^2} C^2) \quad (25)$$

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To transform this right circular cylinder into a parallelepiped, with a square cross-section, which has the same height and volume, all that is necessary is that the cross sectional areas be equal.

That is:

$$\pi R_M^2 = X^2 \quad (26)$$

where X is the length of the side of the square.

Substituting (25) in (26)

$$X = \left[N_{c_{max}} \frac{\sqrt{3}}{4} \left(A^2 + \frac{h_{max}^2}{3H^2} C^2 \right) \right]^{1/2} \quad (27)$$

For the final core the following values were used:

A	=	5.018 in.	=	12.746 cm
B	=	11.000 in.	=	27.94 cm
H	=	300.00 in.	=	762.0 cm
L	=	42.00 in.	=	107.78 cm
L _R	=	60.00 in.	=	152.80 cm
N _{cmax}	=	146 for bare core (fuel section)		
	=	398 for blanketed core		

The values obtained for h_{max} were:

for the fuel section, h_{max} = 106.0 cm

for the blanket section h_{max} = 147.5 cm

for the axial blanket section h_{max} = 151.0 cm

The values of R_M were:

for the fuel section, 57.87 cm

for the radial blanket, 95.56 cm

for the axial solution only the value of x for the fuel section was needed. It was 102.57 cm.

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B. Calculation of Average Densities for the Equal Volume Model

In order to make the mathematical model described correctly the actual core the model densities should be such that the total number of atoms in the model is the same as in the actual core.

These expressions for the material densities are derived as follows:

Atoms of i in the model = Atoms of i in the core

$$\rho_{Mi} V_M = \int_{V_A} \rho_{Ai} dV_A \quad (1)$$

where

ρ_{Mi} = atom density of i in the model

ρ_{Ai} = atom density of i in actual core at elevation h

V_M = volume of model or any section of it

V_A = actual volume being described

$$V_A = \pi R_e^2 h \quad (2)$$

or

$$dV_A = \pi R_e^2 dh \quad (2a)$$

where

R_e = equivalent radius = a function of h

also

$$\rho_{Ai} = \frac{\rho_{wi} N_A A_i}{A_{wi} A_0} \quad (3)$$

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where

ρ_{wi} = density of i in gm/cc at elevation h

N_A = atoms/gm mole

A_0 = area of the cell at elevation h

A_{wi} = gram molecular weight of i

A_i = area of i in cm^2 in a cell at elevation h

also

$$V_M = \pi R_M^2 (\Delta h) \quad (4)$$

Substituting (2a), (3), and (4) in (1)

$$P_{Mi} \pi R_M^2 (\Delta h) = \int_{\Delta h} \frac{\rho_{wi} N_A A_i}{A_{wi} A_0} \pi R_e^2 dh \quad (5)$$

therefore

$$P_{Mi} = \frac{\rho_{wi} N_A}{A_{wi} R_M^2 (\Delta h)} \int_{\Delta h} \frac{A_i R_e^2}{A_0} dh \quad (6)$$

from Appendix A, recall that,

$$R_e^2 = \frac{N_{cat} A_0}{\pi} \quad (7)$$

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where $N_{c\Delta h}$ = number of cells in the section of the core being considered

A_0 = area of unit cell

Substituting (7) in (6) and making $N_{c\Delta h}$ = constant over Δh

$$P_{Mi} = \frac{P_{wi} N_A}{A_{wi} R_M^2 (\Delta h)} \int_{\Delta h} \frac{A_i N_{c\Delta h} A_0}{\pi A_0} dh \quad (8)$$

or

$$P_{Mi} = \frac{P_{wi} N_A N_{c\Delta h}}{A_{wi} R_M^2 (\Delta h) \pi} \int_{\Delta h} A_i dh \quad (8a)$$

As For those materials for which A_i is constant in the volume described by Δh ,

$$\int_{\Delta h} A_i dh = A_i (\Delta h) \quad (9)$$

If A_M = cross-sectional area of the model

$$= \pi R_M^2$$

then, substituting (9) in (8)

$$P_{Mi} = \frac{P_{wi} N_A N_{c\Delta h} A_i}{A_{wi} A_M} \quad (10)$$

For those materials for which A_i is not constant

$$A_i = A_0 - K \quad (11)$$

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where K = the sum of the areas of the other materials
thus,

$$P_{Mi} = \frac{P_{wi} N_A N_{c\Delta h}}{A_{wi} A_M (\Delta h)} \int_{\Delta h} (A_o - K) dh \quad (12)$$

If K is a constant, independent of Δh , and since

$$A_o = \frac{5^2 \sqrt{3}}{4} = \frac{\sqrt{3}}{4} (A^2 + \frac{h^2}{H^2} C^2) \quad (13)$$

then

$$P_{Mi} = \frac{P_{wi} N_A N_{c\Delta h}}{A_{wi} A_M (\Delta h)} \int_{\Delta h} \left[\frac{\sqrt{3}}{4} (A^2 + \frac{h^2}{H^2} C^2) - K \right] dh \quad (14)$$

It can be shown that the integral in (14) reduces to

$$\int_{\Delta h} \left[\frac{\sqrt{3}}{4} (A^2 + \frac{h^2}{H^2} C^2) - K \right] dh = \pi R_M^2 - K N_{c\Delta h} \quad (15)$$

thus
$$P_{Mi} = \frac{P_{wi} N_A}{A_{wi}} \left[1 - \frac{K N_{c\Delta h}}{A_M} \right]$$

A similar method may be used for those cases where K is not a constant, that is when there is more than one material for which A_i is a function of h . However, in this case there was only one material for which A_i varied with h , so the derivation was not extended to the more general case.

APPENDIX (Continued)

For this study, the following constants were used:

Material	ρ_{wi}	A_{wi}
Sodium	.823	23
Stainless Steel(Fe)	8.03	55.85
UC	13.6	249.5 (Varied depending upon enrichment)

$$N_A = 0.6023 \times 10^{-24}$$

Minor corrections were also made to account for the materials in the control rod cells, although the control poisons were omitted.

C. The Correction to the GNU Conversion Ratio to Account for U-238 Fissions

In the GNU program the conversion ratio is defined as the ratio of absorptions in fertile material to absorptions in fuel material. A better definition would be the ratio of non-fission absorptions in fertile material to absorptions in fuel material.

The fission absorptions in fertile material may be calculated as follows, using data from the GNU output and values of ν_g and $(\nu\sigma)_{fg}$ for the fertile material.

For any lethergy group

$$Abs_g = \bar{\phi}_g \sum a_g \quad (1)$$

Since Abs_g and $\sum a_g$ are given in the GNU output then

$$\bar{\phi}_g = \frac{Abs_g}{\sum a_g} \quad (1a)$$

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Fission absorptions are calculated from

$$F_g = \bar{\phi}_g \frac{(\bar{\nu} \sigma_f)_g}{\bar{\nu}_g} N \quad (2)$$

where $(\bar{\nu} \sigma_f)_g$ values were from the AETR cross-section data book, $\bar{\nu}_g$ was estimated from the "Six Group Cross-Sections" (Los Alamos, N-2-731), and N is the atom density of fertile material. Because of the method of normalization used by GNU, equation (2) is dimensionally correct and has the same units as the absorptions given in the GNU output.

Thus, the corrected conversion ratio is

$$CR = \frac{Abs_{fertile} - \sum_g \bar{\phi}_g \frac{(\bar{\nu} \sigma_f)_g}{\bar{\nu}_g} N_{fertile}}{Abs_{fuel}} \quad (3)$$

The values used for $\bar{\nu}_g$ and $(\bar{\nu} \sigma_f)_g$ are given below:

Lethergy Group (g)	$\bar{\nu}_g$	$(\bar{\nu} \sigma_f)_g$
1	2.80	2.489
2	2.80	1.506
3	2.62	1.519
4	2.48	1.100
5	2.00	.117
6	1.00	.005
7 thru thermal	0	0

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