UNITED STATES ATOMIC ENERGY COMMISSION

CALCULATION OF EFFECT OF FUEL BURNUP
ON FUEL AND POISON DISTRIBUTIONS AND
ON FLUX DISTRIBUTION IN THE MARINE
REACTOR

Project 16

By
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January 29, 1957

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for Pure and Applied Science

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AND ON FLUX DISTRIBUTION IN THE MARINE REACTOR

Work done by:
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Report written by:
George Hinman

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Project 16

January 29, 1957

CALCULATION OF EFFECT OF FUEL BURNUP ON FUEL AND POISON DISTRIBUTIONS AND ON FLUX DISTRIBUTION IN THE MARINE REACTOR

One of the design requirements of the maritime reactor is a long operational period between refuelings. It follows directly from this that the change in fuel inventory during the period of operation will be large with a correspondingly large change in the contribution of the fuel to the reactivity of the reactor core. In order to partially compensate for this change it is proposed to introduce a burnable poison into the core which will burn out at approximately the same rate as the U^{235} fuel.

The purpose of the present work is to study roughly the changes in fuel and poison distributions and the changes in flux shape which accompany the consumption of fuel. The technique employed is a perturbation calculation based on a one-velocity group treatment of the neutrons. The equations for the neutron flux in this case are:

In the core--

$$D\Delta\phi - \Sigma\phi + \nu\psi\phi = 0 \quad (1)$$

In the reflector--

$$D(C)\Delta\phi - \Sigma(C)\phi = 0 \quad (2)$$

where ϕ = neutron flux.

D = diffusion constant in the core.

Σ = macroscopic absorption cross section in the core.

ν = number of neutrons per fission.

$\psi = \sigma_f(U^{235})N(U^{235})$ = macroscopic fission cross section of U^{235} .

$\sigma_f(U^{235})$ = microscopic fission cross section of U^{235} .

$N(U^{235})$ = number of U^{235} atoms per cm^3 .

$D(C)$ = diffusion constant in reflector.

$\Sigma(C)$ = macroscopic cross section in reflector.

The geometrical configuration chosen is a spherical core surrounded by an infinite reflector. Spherical symmetry is assumed and therefore only the radial variable r is important. The equations for ϕ in this case reduce to

In the core--

$$D \frac{d^2(r\phi)}{dr^2} + (\nu\psi - \Sigma)r\phi = 0 \quad (3)$$

In the reflector--

$$D(C) \frac{d^2(r\phi)}{dr^2} - \Sigma(C)r\phi = 0. \quad (4)$$

The condition that $\phi \rightarrow 0$ as $r \rightarrow \infty$ requires that in the reflector

$$\phi = \frac{Ke^{-\mu r}}{r} \quad (5)$$

where $\mu = \sqrt{\Sigma(C)/D(C)}$

K = constant determined by the power level at which the reactor is operated.

Using this solution in the reflector the continuity requirements on ϕ and $d\phi/dr$ at the core boundary can be replaced by a simple condition on the flux in the core, namely,

$$\frac{\frac{df}{dr}}{f} = -\mu \text{ at } r = a \quad (6)$$

where $f = r\phi$

a = core radius.

The equation for the flux can now be written

$$\frac{d^2 f}{dr^2} + \lambda^2 f = 0 \quad (7)$$

where $\lambda^2 = (\nu\psi - \Sigma)/D$

with the boundary conditions (6) and $f(0) = 0$.

The quantity λ^2 will in general depend on r in a way determined by the distribution of material in the core. It will be assumed, however, that at the beginning of the operational period, λ^2 is independent of r corresponding to a uniform core medium. As the fuel and poison burn out the λ^2 will change and the effects of these changes will be calculated by a perturbation method.

In order to consider equation (7) as an eigenvalue problem let us rewrite it as

$$\frac{d^2 f}{dr^2} + [k^2 - \lambda_1^2(r)] f = 0 \quad (8)$$

where $f(0) = 0$;

$$\frac{df/dr}{f} = -\mu;$$

$$r = a;$$

and where k^2 is the lowest eigenvalue of (8) and

$$\begin{aligned} \lambda_1^2(r) = \frac{1}{D} & \left[\sum_0 (B) (e^{-\sigma_a(B)} \int_0^t \phi(r, t') dt' - 1) \right. \\ & \left. + (\sum_0 (U^{235}) - (\nu \psi)_0) (e^{-\sigma_a(U^{235})} \int_0^t \phi(r, t') dt' - 1) \right]. \end{aligned}$$

At $t = 0$ $\lambda_1^2(r) = 0$ and in this case let us call the lowest eigenvalue λ_0^2 .

The secular equation satisfied by λ_0 is

$$\cot \lambda_0 a = - \frac{\mu}{\lambda_0} \quad (9)$$

with $\lambda_0 a$ in the second quadrant. The initial critical equation for the reactor can be obtained by setting.

$$\lambda_0^2 = \left(\frac{\sum - \nu \psi}{D} \right)_{t=0} \quad (10)$$

and this equation along with (9) relates the core radius to the material properties of the core.

The perturbation method to be applied to (8) requires also the calculation of other eigenvalues which satisfy (9). Calling the second and third eigenvalues $\lambda_0^{(1)}$ and $\lambda_0^{(2)}$ and letting the three normalized eigenfunctions be $f_0(r)$, $f_1(r)$, and $f_2(r)$, a first order perturbation calculation of k^2 in equation (8) gives*

$$k^2 = \lambda_0^2 + U_{00} \quad (11)$$

$$f(r) \approx f_0(r) + \frac{U_{10}}{\lambda_0^2 - (\lambda_0^{(1)})^2} f_1(r) + \frac{U_{20}}{\lambda_0^2 - (\lambda_0^{(2)})^2} f_2(r) \quad (12)$$

where $U_{10} = \int_0^a f_1(r) \lambda_1^2(r) f_0(r) dr.$

The equations above describe the simple perturbation method used in the calculations of burnout for the maritime reactor. A program described below has been written for the IBM-650 which performs the computations using the Wolontis interpretive system.

After a preliminary calculation of various quantities used in equations (1) through (12) from the input data, the quantity λ_0^2 is calculated from equation (10). The critical radius of the core is then found from equation (9) written in the form

$$a = \frac{1}{\lambda_0} \left[\pi - \arctan \left(\frac{\mu}{\lambda_0} \right) \right]. \quad (13)$$

Following these operations λ_0^2 and a are punched out.

As the next step in the calculation approximations for $\lambda_0^{(1)}$ and $\lambda_0^{(2)}$ are found from

$$\lambda_0^{(1)} \approx \frac{3\pi}{2a} \quad (14)$$

$$\lambda_0^{(2)} \approx \frac{5\pi}{2a} \quad (15)$$

*Morse and Feshbach, V. II, p. 1004.

Then the eigenfunctions $f_0(r)$, $f_1(r)$, and $f_2(r)$, normalized so that $\int_0^a f_1^2 dr = 1$, are tabulated in storage locations within the computer at intervals ($\Delta r = a/M_0$) from $r = 0$ to $r = a$.

At this point the program calls for the computation and punching of certain reactor properties at the beginning of the operational period. These properties include first of all k^2 , $k^2 - \lambda_0^2$, $k_{\infty} - 1 \equiv k^2 \frac{D}{\sum_0}$ (where $\sum_0$ is the initial total macroscopic absorption coefficient), and $k_{\infty} - k_{\infty 0}$ (where $k_{\infty 0}$ is the initial value of $k_{\infty} = \lambda_0^2 \frac{D}{\sum_0}$). Initially $k^2 = \lambda_0^2$, $k^2 - \lambda_0^2 = 0$, $k_{\infty} - 1 = \lambda_0^2 \frac{D}{\sum_0}$, and $k_{\infty} - k_{\infty 0} = 0$.

Other properties computed and punched at this point as functions of r are the initial values of $\phi(r)/\phi(\Delta r)$, $N(B)/N_0(B)$, and $N(U^{235})/N_0(U^{235})$ [$N(B)$ = number of boron atoms per cm^3 , $N_0(B)$ = initial number of boron atoms per cm^3 , $N(U^{235})$ = number of U^{235} atoms per cm^3 , $N_0(U^{235})$ = initial number of U^{235} atoms per cm^3 , $\phi(\Delta r)$ = (neutron flux at $r = \Delta r$)]. The ratio $\phi(r)/\phi(\Delta r)$ is used rather than $\phi(r)/\phi(0)$ because the evaluation of $\phi(0)$ involves the indeterminate form $0/0$. Initially, of course, $N(B)/N_0(B) = 1$ and $N(U^{235})/N_0(U^{235}) = 1$ for all r .

The rest of the program concerns itself with changes in k^2 , $k^2 - \lambda_0^2$, $k_{\infty} - 1$, $k_{\infty} - k_{\infty 0}$, $\phi(r)/\phi(\Delta r)$, $N(B)/N_0(B)$, and $N(U^{235})/N_0(U^{235})$ as the reactor fuel is consumed. Changes in the amount of fuel present are assumed to take place stepwise rather than continuously. Each of these changes reduces the amount of fuel in the center of the reactor core by a factor $e^{-.05}$. It therefore reduces the amount of boron by a factor $e^{-[\sigma_a(B)/\sigma_a(U^{235})] \cdot .05}$. In order to calculate the corresponding changes at other points in the core the flux distribution before the change occurs is used.

After the new fuel and poison distributions have been calculated at all radii using the flux shape before the change, a new flux shape is computed by the

machine from equation (12). A new value of k^2 is found from equation (11) and from it new results for $k^2 - \lambda_0^2$, $k_\infty - 1$, and $k_\infty - k_{0\infty}$.

This completes one cycle in the program and after punching the new values of the reactor properties, the fuel in the center is again changed and the calculations are repeated. The machine stops after a prescribed number of fuel changes.

Description of Input and Output Data from the Machine

It is assumed that the materials present in the reactor core are Zr, H, B, Fe, U^{235} , U^{238} , O. If desired, these can be changed (with the exception of the U^{235} , of course) so long as the number of elements does not exceed seven.

Table 1 shows the locations into which numbers must initially be loaded when using the machine. The number $\bar{N}(U^{235})$ in location 911 is larger than $N(U^{235})$ to include absorption of neutrons by the fission products Xe and Sm. $N(U^{235})$ is used in calculating such quantities as ψ which are sources rather than sinks of neutrons and to which the Xe and Sm poisons do not contribute. The number M_0 in location 920 is the number of intervals into which the core radius a is to be divided when performing the calculations. In location 921 is t_{final} which is the final value of $\phi_a(U^{235}) \int_0^t \phi(0, t') dt'$ desired in the calculation. The change in this quantity from one stage in the calculation to the next is Δt located in 954.

The output from the calculation has been described on pages 5 and 6 of this report. A brief summary of the output cards is given below.

	<u>Word 1</u>	<u>Word 2</u>	<u>Word 3</u>	<u>Word 4</u>	
Card 1	λ_0^2	--	--	--	
Card 2	a	--	--	--	
Card 3	k^2	$k^2 - \lambda_0^2$	$k_\infty - 1$	$k_\infty - k_{0\infty}$	} Initial Values
Card 4 through Card(4+ M_0)	r	$\frac{\phi(r)}{\phi(\Delta r)}$	$\frac{N(B)}{N_0(B)}$	$\frac{N(U^{235})}{N_0(U^{235})}$	

TABLE 1

7

COMPUTING CENTER				PROGRAMMING FORM				WOLONTIS SYS., I.B.M. 630				PROGRAMMER			
INPUT REQUIRED FOR BURNOUT PROGRAM												PROBLEM			
1-4 5-6 7-9 10				11				76: CARD COLUMNS							
CARD No.	DK No.	LOC. WD.1	N	DRM. LOC.	OP: NO.	+	0	AOR ₂	B	C	COMMENTS				
						-	X.XXX,XXX,X; a								
				900				$\sigma_a(\text{Zr})$			absorption cross section of Zr in cm^2				
				901				$\sigma_a(\text{H})$			absorption cross section of H in cm^2				
				902				$\sigma_a(\text{B}^{10})$			absorption cross section of B^{10} in cm^2				
				903				$\sigma_a(\text{Fe})$			absorption cross section of Fe in cm^2				
				904				$\sigma_a(\text{U}^{235})$			absorption cross section of U^{235} in cm^2				
				905				$\sigma_a(\text{U}^{238})$			absorption cross section of U^{238} in cm^2				
				906				$\sigma_a(\text{O})$			absorption cross section of O in cm^2				
				907				$N(\text{Zr})$			number atoms Zr per cm^3				
				908				$N(\text{H})$			number atoms H per cm^3				
				909				$N(\text{B}^{10})$			number atoms B^{10} per cm^3				
				910				$N(\text{Fe})$			number atoms Fe per cm^3				
				911				$N(\text{U}^{235})$			augmented no. atoms U^{235} per cm^3				
				912				$N(\text{U}^{238})$			number atoms U^{238} per cm^3				
				913				$N(\text{O})$			number atoms O per cm^3				
				914				$\sigma_a(\text{C})$			absorption cross section reflector in cm^2				
				915				$N(\text{C})$			number atoms reflector per cm^3				
				916				$D(\text{C})$			diffusion constant reflector in cm				
				917				$\sigma_f(\text{U}^{235})$			fission cross section U^{235} in cm^2				
				918				$\nu(\text{U}^{235})$			number of neutrons per fission in U^{235}				
				919				D			diffusion constant of core				
				920				Mo							
				921				t_{final}							
				922				$N(\text{U}^{235})$			number of atoms U^{235} per cm^3				
				950			+	0	000	000	0.00				
				951			+	1	000	000	0.50				
				952			+	3	141	600	0.50				
				953			+	2	000	000	0.50				
				954				Δt							
				955			+	1	500	000	0.50				
				956			+	2	500	000	0.50				
				957			+	1	000	000	0.01				

Cards are then punched in groups of M_0+2 with the same format as cards 3 through $4+M_0$ but giving the quantities listed at later stages of fuel burnup. The calculation of $\phi(0)/\phi(\Delta r)$ should be disregarded.

Sample Calculations Using the Code

Two sample calculations have been worked out using the code described above. The values of the constants used, and the results, are plotted on graphs 1 through 6. The curves show that the consumption of fuel and poison does not greatly affect the shape of the flux distribution. Therefore, further effects of burnup can be calculated to a good approximation with the assumption that the flux distribution does not change as the fuel and poison are used up. Curves 2 and 5 show the changes in the reactivity of the core as the burnout continues. A positive ordinate means that control rods must be inserted into the reactor to prevent its becoming supercritical. A negative one calls for more reactivity than was originally present. If it is desired to continue operation into this negative region, it is necessary to make provision for it initially by including some neutron absorption in control rods inserted into the core at the beginning of the operating period. Such absorption can be introduced into the code, for example, by using the locations designated $\sigma_a(0)$ and $N(0)$ because the oxygen has an insignificant effect on the reactivity of the core.

It should be remembered that the one-group theory employed in this calculation will not in general give a close value of theoretical radius a . On the other hand, it should provide fairly good information on the fuel and poison burnup and the change in flux shape as this burnup takes place.

LIST OF PARAMETERS FOR CASES INVESTIGATED

Case 1. (see curves 1-3)

$$\sigma_a (\text{Zr}) = 8.30 \times 10^{-26} \text{ cm}^2$$

$$\sigma_a (\text{H}) = 1.50 \times 10^{-25} \text{ cm}^2$$

$$\sigma_a (\text{B}) = 21 \times 10^{-21} \text{ cm}^2$$

$$\sigma_a (\text{SS}) = 1.16 \times 10^{-24} \text{ cm}^2$$

$$\sigma_a (\text{U}^{235}) = 2.93 \times 10^{-22} \text{ cm}^2$$

$$\sigma_a (\text{U}^{238}) = 1.28 \times 10^{-24} \text{ cm}^2$$

$$\sigma_a (0) = 0$$

$$N (\text{Zr}) = 1.93 \times 10^{22}$$

$$N (\text{H}) = 2.32 \times 10^{22}$$

$$N (\text{B}) = 1.30 \times 10^{19}$$

$$N (\text{SS}) = 2.77 \times 10^{22}$$

$$\bar{N} (\text{U}^{235}) = 3.82 \times 10^{20}$$

$$N (\text{U}^{235}) = 3.61 \times 10^{20}$$

$$N (0) = 0$$

$$N (\text{U}^{238}) = 8.90 \times 10^{20}$$

$$\sigma_a (\text{C}) = 3.20 \times 10^{-27}$$

$$N (\text{C}) = 8.30 \times 10^{22}$$

$$D (\text{C}) = 20.0$$

$$\sigma_f (\text{U}^{235}) = 2.50 \times 10^{-22} \text{ cm}$$

$$\nu (\text{U}^{235}) = 2.45$$

$$D = 80$$

$$t_{\text{final}} = .50$$

$$\left(\frac{N (\text{U}^{235}) \text{ at } r = 0}{N_0 (\text{U}^{235}) \text{ at } r = 0} = e^{-.50} \right)$$

$$a = 74.0 \text{ cm}$$

Case 2. (see curves 4-6)

All parameters the same

as Case 1. except as follows:

$$\nu = 2.20$$

$$a = 110.6 \text{ cm}$$

$$t_{\text{final}} = .50$$

COMPUTING CENTER				PROGRAMMING FORM				PROGRAMMER			
				WOLONTIS SYS., I.B.M. 650				Hinman			
EFFECT OF FUEL BURNUP ON FUEL & POISON DISTRIBUTIONS AND FLUX DISTRIBUTION				PROBLEM							
I-4 5,6 7-9 10				II				76 CARD COLUMNS			
CARD No.	DK No.	LOC. WD.1	N	DRM. LOC.	OP: NO:	+	O ₁	AOR O ₂	B	C	COMMENTS
						-	X.XXX.XXX.X; a				
0001	01	050	6	050		+	3	917	918	0 00	$(\psi)_0 \rightarrow 816$
				051		+	3	000	922	8 16	
				052		+	3	904	911	8 15	$\sum_0 (U^{235}) \rightarrow 815$
				053		+	3	902	909	8 14	$\sum_0 (B) \rightarrow 814$
				054		+	9	000	950	8 13	$t = 0 \rightarrow 813$
				055		-	9	000	951	5 00	$\frac{N(B)}{N_0(B)} = 1 \cdot \frac{N(U^{235})}{N_0(U^{235})} = 1 \rightarrow 50X$
0002	01	056	6	056		+	0	001	100	0 55	$N_0(B) \quad N_0(U^{235}) \quad 55X$
				057		+	3	917	922	8 00	$\psi \rightarrow 800$
				058		+	9	000	950	8 01	$0 \rightarrow 801$
				059		-	3	900	907	0 00	
				060		+	1	000	801	8 01	$\sum_0 \rightarrow 801$
				061		+	0	110	007	0 59	
0003	01	062	6	062		+	4	919	801	8 26	$\sum_0 \rightarrow 826$
				063		+	3	918	800	0 00	
				064		+	2	000	801	0 00	$\lambda_0^2 \rightarrow 802$
				065		+	4	000	919	8 02	
				066		+	0	300	000	8 03	$\lambda \rightarrow 803$
				067		+	3	914	915	0 00	$\mu^2 \rightarrow 804$
0004	01	068	6	068		+	4	000	916	8 04	
				069		+	0	300	000	8 05	$\mu \rightarrow 805$
				070		+	4	803	805	0 00	
				071		+	0	305	000	0 00	
				072		+	5	000	951	0 00	$a \rightarrow 806$
				073		+	1	000	952	0 00	
0005	01	074	6	074		+	4	000	803	8 06	
				075		+	3	953	803	0 00	$2\lambda_0 a \rightarrow 807$
				076		+	3	000	806	8 07	
				077		+	4	806	920	8 10	$\Delta r \rightarrow 810$
				078		+	4	000	953	8 18	$\Delta^r/2 \rightarrow 818$
				079		+	4	953	806	8 63	$^2/a \rightarrow 863$
0006	01	080	6	080		+	0	300	000	8 64	$\sqrt{2/a} \rightarrow 864$
				081		+	0	303	807	0 00	
				082		+	4	000	807	0 00	$A^2 \rightarrow 808$
				083		+	2	951	000	0 00	
				084		+	4	863	000	8 08	
				085		+	0	300	000	8 09	$A \rightarrow 864$

COMPUTING CENTER				PROGRAMMING FORM				HINMAN		PROGRAMMER	
				WOLONTIS SYS., I.B.M. 650						PROBLEM	
EFFECT OF FUEL BURNUP ON FUEL & POISON DISTRIBUTIONS AND FLUX DISTRIBUTION											
1-4 5,6 7-9 10				11				76: CARD COLUMNS			
CARD No.	DK No.	LOC. WD.1	N	DRM. LOC.	OP: NO:	+	O ₁	AOR O ₂	B	C	COMMENTS
						-	X.XXX,XXX,X			a	
0007	01	086	6	086		+	3	810	803	8 11	$\lambda_0 \Delta r \rightarrow 811$
				087		+	3	803	806	8 12	$\lambda_0 a \rightarrow 812$
				088		+	0	410	802	8 02	PUNCH λ_0^2
				089		+	0	410	806	8 06	PUNCH a
				090		+	2	815	816	8 17	$\sum_0 (U) - (\nu\psi)_0 \rightarrow 817$
				091		+	3	955	952	0 00	$3\pi/2a \rightarrow 857$
0008	01	092	6	092		+	4	000	806	8 57	
				093		+	3	000	810	8 58	$(3\pi/2a) \Delta r \rightarrow 858$
				094		+	3	956	952	0 00	$5\pi/2a \rightarrow 859$
				095		+	4	000	806	8 59	
				096		+	3	000	810	8 60	$(5\pi/2a) \Delta r \rightarrow 860$
				097		+	9	000	951	8 65	Zero test box 1 $\rightarrow 865$
0009	01	098	6	098		+	9	000	950	8 61	$(3\pi/2a) r = 0 \rightarrow 861$
				099		+	9	000	950	8 62	$(5\pi/2a) r = 0 \rightarrow 862$
				100		+	9	000	950	8 50	$\lambda_0 r = 0 \rightarrow 850$
				101		+	0	005	107	7 50	
				102		+	0	005	109	3 50	Sets
				103		+	0	005	111	4 00	
0010	01	104	6	104		+	0	005	106	3 00	
				105		+	0	303	850	0 00	
				106		+	3	000	809	(3 00)	$f_0(r) \rightarrow 30X$
				107		+	9	000	000	(7 50)	$f(r) = f_0(r) \rightarrow 75X$
				108		+	0	303	861	0 00	
				109		+	3	000	864	(3 50)	$f_1(r) \rightarrow 35X$
0011	01	110	6	110		+	0	303	862	0 00	
				111		+	3	000	864	(4 0X)	$f_2(r) \rightarrow 40X$
				112		+	2	920	865	0 00	
				113		+	0	201	114	1 23	Test
				114		+	1	865	951	8 65	
				115		+	0	006	106	0 01	
0012	01	116	6	116		+	0	006	107	0 01	
				117		+	0	006	109	0 01	Increases
				118		+	0	006	111	0 01	
				119		+	1	850	811	8 50	
				120		+	1	861	858	8 61	
				121		+	1	862	860	8 62	

COMPUTING CENTER				PROGRAMMING FORM								PROGRAMMER	
				WOLONTIS SYS., I.B.M. 650								Hinman	
EFFECT OF FUEL BURNUP ON FUEL & POISON DISTRIBUTIONS AND FLUX DISTRIBUTION												PROBLEM	
I-4 5,6 7-9 10				II-76 CARD COLUMNS									
CARD No.	DK. No.	LOC. WD.1	N	DRM. LOC.	OP. NO.	+	0	AOR	O ₂	B	C	COMMENTS	
						-	X	XXX	XXX	X	a		
0013	01	122	6	122		+	0	203	000	1	05	Transfer back	
				123		+	9	000	802	8	27	$k^2 = \lambda^2 \rightarrow 827$	
				124		+	9	000	950	8	28	$k^2 - \lambda^2 = 0 \rightarrow 828$	
				125		+	9	000	950	8	30	$k_{\infty} - k_0 \rightarrow 830$	
				126		+	3	827	826	8	29	$k_{\infty} - 1 \rightarrow 829$	
				127		+	4	902	904	0	00		
0014	01	128	6	128		+	3	000	954	8	19		
				129		+	3	857	857	8	67		
				130		+	3	859	859	8	68	Initial calculations end here	
				131		+	4	751	810	8	53	$\frac{f(\Delta r)}{\Delta r} \rightarrow 853$	
				132		+	0	050	141	5	50	SET	
				133		+	0	410	827	8	30	PUNCH $k^2, k^2, \lambda^2, k_{\infty} - 1, k_{\infty} - k_0$	
0015	01	134	6	134		+	9	000	951	8	65	RESET TEST BOX	
				135		+	9	000	957	8	32	$r = 10^{-49} \rightarrow 832$	
				136		+	0	500	154	7	50		
				137		+	0	050	140	5	00	SETS	
				138		+	0	005	155	7	50		
				139		+	0	203	000	1	54		
0016	01	140	6	140		+	9	000	(500)	8	34	MOVE $\phi(r), N(B), N(u)$ $\phi(Ar), N_0(B), N_0(u)$	
				141		+	9	000	(550)	8	35	TO PUNCH LOCATIONS	
				142		+	0	410	832	8	35	PUNCH $r, \phi(r), N(B), N(u)$ $N_0(B), N_0(u)$	
				143		+	2	920	865	0	00	TEST	
				144		+	0	201	145	1	58		
				145		+	1	865	951	8	65		
0017	01	146	6	146		+	1	832	810	8	32		
				147		+	0	600	154	0	01	INCREASES	
				148		+	0	060	140	0	01		
				149		+	0	060	141	0	01		
				150		+	0	006	155	0	01	TRANSFER	
				151		+	0	203	000	1	54	Tabulation of values ends here	
0039	01	154	4	152									
				153									
				154		+	4	(750)	832	0	00		
				155		+	4	000	853	(7	50)		
				156		+	9	000	000	8	33		
				157		+	0	203	000	1	40		

COMPUTING CENTER				PROGRAMMING FORM								PROGRAMMER	
				WOLONTIS SYS., I.B.M. 650								HINMAN	
EFFECT OF FUEL BURNUP ON FUEL & POISON DISTRIBUTIONS AND FLUX DISTRIBUTION												PROBLEM	
1-4 5-6 7-9 10				11-76 CARD COLUMNS									
CARD No.	CHK No.	LOC. WD.1	N	DRM. LOC.	OP: NO.	+	0	A	RO ₂	B	C	COMMENTS	
						-	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX		
0018	01	158	4	158		+	1	813	954	8	13	Increase t	
				159		+	2	921	813	0	00	Test t > t _p	
				160		+	0	201	170	1	61		
				161		+	0	000	000	0	00	STOP if t > t _p	
				162								TEST FOR END OF CALCULATION	
				163								ENDS HERE	
				164									
				165									
				166									
				167									
				168									
				169									
0019	01	170	6	170		+	9	000	951	8	65	SET TEST BOX	
				171		+	0	050	212	4	01		
				172		+	0	500	212	3	01		
				173		+	9	000	950	8	23		
				174		+	0	050	209	3	51		
				175		+	0	500	209	3	01		
0020	01	176	6	176		+	9	000	950	8	22		
				177		+	0	050	206	3	01		
				178		+	0	500	206	3	01		
				179		+	9	000	950	8	21	INITIALIZATION	
				180		+	0	500	202	5	51		
				181		+	0	500	200	5	01		
0021	01	182	6	182		+	0	005	199	5	01		
				183		+	0	050	199	5	01		
				184		+	0	050	196	7	51		
				185		+	0	005	195	5	51		
				186		+	0	050	195	5	51		
				187		+	0	050	192	7	51		
0022	01	188	6	188		+	0	301	954	0	00	Modify $e^{-\sigma_a(u)} \int_0^t \phi(o, t') dt'$	
				189		+	4	550	000	5	50		
				190		+	0	301	819	0	00	Modify $e^{-\sigma_a(B)} \int_0^t \phi(o, t') dt'$	
				191		+	4	500	000	5	00		
				192		+	5	954	(751)	0	00	See next page	
				193		+	4	000	751	0	00		

COMPUTING CENTER				PROGRAMMING FORM				WOLONTIS SYS., I.B.M. 650				Hinman				PROGRAMMEN							
EFFECT OF FUEL BURNUP ON FUEL & POISON DISTRIBUTIONS AND FLUX DISTRIBUTION												PROBLEM											
I-4				5-6				7-9				10				II				7-6 CARD COLUMNS			
CARD No.	DK No.	LOC. WD.1	N	DRM. LOC.	OP. NO.	+	0	A	PRO	B	C	COMMENTS											
												X.XXX,XXX,X	a										
0023	01	194	6	194		+	0	301	000	0	00	Modify $e^{-\sigma_a(U)} \int_0^t \phi(r,t') dt'$											
				195		+	3	000	(551)	(5	51)												
				196		+	5	819	(751)	0	00												
				197		+	4	000	751	0	00	Modify $e^{-\sigma_a(B)} \int_0^t \phi(r,t') dt'$											
				198		+	0	301	000	0	00												
				199		+	3	000	(501)	(5	01)												
0024	01	200	6	200		+	2	(501)	951	0	00												
				201		+	3	000	814	8	51)												
				202		+	2	(551)	951	0	00												
				203		+	3	000	817	8	52)	New $\lambda_1^2(r) \rightarrow 820$											
				204		+	1	851	852	0	00												
				205		+	4	000	919	8	20)												
0025	01	206	6	206		+	3	(301)	(301)	0	00												
				207		+	3	000	820	0	00	ACCUMULATE $\int_0^t \lambda_1^2 f_0 dr$											
				208		+	1	000	821	8	21)												
				209		+	3	(301)	(351)	0	00												
				210		+	3	000	820	0	00	ACCUMULATE $\int_0^t \lambda_1^2 f_1 dr$											
				211		+	1	000	822	8	22)												
0026	01	212	6	212		+	3	(301)	(401)	0	00												
				213		+	3	000	820	0	00	ACCUMULATE $\int_0^t \lambda_1^2 f_0 dr$											
				214		+	1	000	823	8	23)												
				215		+	2	865	920	0	00	TEST											
				216		+	0	201	233	2	17)												
				217		+	1	951	865	8	65)												
0027	01	218	6	218		+	0	060	212	0	01												
				219		+	0	600	212	0	01												
				220		+	0	060	209	0	01												
				221		+	0	600	209	0	01												
				222		+	0	060	206	0	01												
				223		+	0	600	206	0	01	INCREASES											
0028	01	224	6	224		+	0	600	202	0	01												
				225		+	0	600	200	0	01												
				226		+	0	006	199	0	01												
				227		+	0	060	199	0	01												
				228		+	0	060	196	0	01												
				229		+	0	006	195	0	01												

GENERAL ATOMIC
Division of General Dynamics Corporation

John Jay Hopkins Laboratory
for Pure and Applied Science

AECU-3596
(Supplement)

CALCULATION OF EFFECT OF FUEL BURNUP ON FUEL AND POISON DISTRIBUTIONS
AND ON FLUX DISTRIBUTION IN THE MARINE REACTOR

Work done by:
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Report written by:
George Hinman

Work performed under Contract No. AT(04-3)-118

Project 16

March 26, 1958

This report is a supplement to Report No. AECU-3596 describing the effect of fuel burnup on fuel and poison distributions and on flux distribution in the marine reactor. It briefly summarizes later thinking about the problem, which differs considerably from that in AECU-3596.

Report AECU-3596 is a one-group calculation. It therefore couples absorption of the single energy neutrons at a point in the core with their production at the same point. This leads to the consequence that reducing the fuel density at a point results in a depression of the flux in the vicinity of the point. In contrast to this, the situation for thermal neutron absorption and fast neutron production in the core is quite different. A local reduction in fuel density in this case increases the thermal flux in the vicinity because thermal absorption is reduced without a compensating loss in production of thermals. The thermal neutrons in this case come principally from the slowing down of fast neutrons produced at surrounding points where the thermal distribution is little affected.

Thus the treatment in AECU-3596 will not give correctly the effect of fuel changes on flux distribution for a thermal reactor. It should be more applicable to burnup in a fast reactor.

For those intending to use the method in AECU-3596 the following remarks should be noted:

1. Equation (13) should read

$$a = \frac{1}{\lambda_0} \left[\pi - \arccot \left(\frac{\mu}{\lambda_0} \right) \right]$$

2. The assumption is made in writing Equation (6) that $D(C) = D$. This restriction can be removed by replacing Equation (6) by a more complicated boundary condition.

3. D is assumed not to vary as the burnup proceeds.