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MASTER

TISE APEX-393

(XDC 58-7-75)

XDC 58-7-75

CELL REMOVAL PROGRAM (704 PROGRAM DELTA)

(JOB NO. 51338)

M. J. Stanley

D. S. Selengut

REACTOR PHYSICS UNIT

June 19, 1958

GENERAL ELECTRIC-AIRCRAFT NUCLEAR PROPULSION DEPARTMENT-CINCINNATI 15, OHIO

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ABSTRACT OF REPORT NO. XDC 58-7-75

TITLE: Cell Removal Program (704 Program DELTA)

AUTHORS AND ORIGINATING UNIT: M. J. Stanley and D. S. Selengut, Reactor Physics

DATE: June 19, 1958

This report describes the theory, input data and output data for 704 Program DELTA. Program DELTA calculates the effect on reactivity of replacing a longitudinal cell which is a distance, r , from the axis of a cylindrical reactor with a cell of different composition. The calculation is made by means of first order perturbation theory on the basis of a two-energy-group diffusion theory.

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ANP 704 Digital Program 152

1. ANP 704 DIGITAL PROGRAM

<u>Title</u>	<u>Engineer</u>	
DELTA	Mary Stanley	Reactor Physics Unit
	D. S. Selengut	HAPO
<u>Computer</u>	<u>Status</u>	<u>Category</u>
704 any size memory no drums required	Checked out	Reactors
Output: Tape 3		
Coded in FORTRAN ¹		

Abstract: This report describes the theory, input data and output data for 704 Program DELTA. Program DELTA calculates the effect on reactivity of replacing a longitudinal cell which is a distance, r , from the axis of a cylindrical reactor with a cell of different composition. The calculation is made by means of first order perturbation theory on the basis of a two-energy-group diffusion theory.

¹ "FORTRAN Automatic Coding System for the IBM 704", International Business Machines Corporation, 590 Madison Avenue, New York 22, New York, December, 1957.

2. INTRODUCTION

This program calculates the effect on reactivity of replacing a longitudinal cell which is a distance, r , from the axis of a cylindrical reactor with a cell of different composition (vacuum, control rod, etc.). The calculation is made by means of first order perturbation theory on the basis of a two-energy-group diffusion theory model.

The reactor may have up to 10 radial regions, which may include fissionable material. There is no provision for longitudinal variation in composition, e.g. no end reflector. However, the perturbation calculation can be made for a partially withdrawn cell.

3. GLOSSARY

<u>Mathematical Symbol</u>	<u>FORTTRAN Mnemonic</u>	<u>Definition</u>
D_1	C(1,J)	fast group
D_2	C(2,J)	thermal group
Σ_{a1}	C(3,J)	fast group
Σ_{a2}	C(4,J)	thermal group
$\nu\Sigma_{f1}$	C(5,J)	fast group
$\nu\Sigma_{f2}$	C(6,J)	thermal group
		} diffusion coefficient
		} absorption probability per unit path length
		} fission probability per unit path length times average neutron production per fission
Σ_{s1}	C(7,J)	slowing-down probability per unit path length from fast group to thermal group
R_j	C(8,J)	outer radius of region J
	where J = 1,M	
d	DCELL	cell diameter in cm
j	-	neutron current
j^+	-	neutron adjoint current
k	REAC	system multiplication before cell replacement
m	M	number of reactor regions including the cell as a separate region
n	N	number of radial lattice points at which the fluxes are specified
r_i	R(I)	radial distance of each lattice point from the axis of the reactor in cm

Mathematical Symbol	FORTTRAN Mnemonic	Definition
z_1	Z1	length of cell withdrawn in cm
z_2	Z2	one-half core length in cm
$1/2 \delta$	DEE	one-group extrapolation distance in cm
$\phi_1(r_i)$	PHI1(I)	fast flux
$\phi_2(r_i)$	PHI2(I)	thermal flux
$\phi_1^+(r_i)$	APHI1(I)	fast adjoint flux
$\phi_2^+(r_i)$	APHI2(I)	slow adjoint flux

} at each lattice point

4. DERIVATION OF EQUATIONS PROGRAMMED

If the linear operators H and K in the eigenvalue equation $H\phi - \lambda K\phi = 0$ are subject to an arbitrary perturbation, one can find the fractional change in the eigenvalue λ as follows.

Multiplying both sides of the equation by the adjoint flux, ϕ^+ , and taking the derivative with respect to ϕ one gets

$$\delta_\phi[\phi^+ H \phi - \lambda \phi^+ K \phi] = [\phi^+ H - \lambda \phi^+ K] \delta \phi = 0. \quad (1)$$

Since $\delta \phi$ can vary over all values,

$$\phi^+ H - \lambda \phi^+ K = 0 \text{ when } \delta \phi = 1. \quad (2)$$

Equation (2) defines the adjoint flux ϕ^+ .

Now assume arbitrary perturbations H' , λ' , K' and ϕ' . Forming perturbed equations,

$$\phi^+ H' \phi' = \lambda' \phi^+ K' \phi', \quad (3)$$

$$\phi^+ H \phi' = \lambda \phi^+ K \phi'. \quad (4)$$

Subtracting equation (4) from equation (3),

$$\phi^+ (H' - H) \phi' = \phi^+ (\lambda' K' - \lambda K) \phi', \quad (5)$$

$$\phi^+ \Delta H \phi' = \phi^+ [(\lambda + \Delta \lambda)(K + \Delta K) - \lambda K] \phi', \quad (6)$$

$$\phi^+ \Delta H \phi' = \phi^+ [\lambda K + \Delta \lambda K + \Delta \lambda \Delta K + \lambda \Delta K - \lambda K] \phi', \quad (7)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{(\phi^+ \Delta H \phi') - \lambda(\phi^+ \Delta K \phi')}{\lambda(\phi^+ K \phi' + \phi^+ \Delta K \phi')} \quad (8)$$

Since $H\phi = \lambda K\phi$, $\lambda K = H$.

$$\frac{\Delta\lambda}{\lambda} = \frac{(\phi^+ \Delta H \phi') - \lambda(\phi^+ \Delta K \phi')}{(\phi^+ H \phi') + \lambda(\phi^+ \Delta K \phi')} \quad (9)$$

Equation (9) is an exact expression for the fractional change in λ .

For the case of two-group theory it is convenient to take

$$\lambda = k, \quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad \phi^+ = \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix},$$

$$H = \begin{pmatrix} \nu \Sigma_{f1} & \nu \Sigma_{f2} \\ 0 & 0 \end{pmatrix}, \quad \text{and } K = \begin{pmatrix} -\nabla \cdot D_1 \nabla + \Sigma_{a1} + \Sigma_{s1} & 0 \\ -\Sigma_{s1} & -\nabla \cdot D_2 \nabla + \Sigma_{a2} \end{pmatrix},$$

so that the inner product becomes the integral of the scalar product of two-component vectors. Equation (9) can then be written as

$$\frac{\Delta k}{k} = \frac{\frac{(\phi^+ \Delta H \phi')}{(\phi^+ H \phi')} - k \frac{(\phi^+ \Delta K \phi')}{(\phi^+ H \phi')}}{1 + k \frac{(\phi^+ \Delta K \phi')}{(\phi^+ H \phi')}} \quad (9a)$$

The second term in the denominator is usually neglected in perturbation theory. It may be important if a large change in reactivity occurs even though the fluxes do not change appreciably.

Neglecting changes in the flux and current, the fractional change in reactivity can be written in terms of the unperturbed current and flux.

$$(\phi^+ \Delta H \phi') \approx \int dv_{\text{cell}} [\phi_1^+ \Delta(\nu \Sigma_{f1}) \phi_1 + \phi_1^+ \Delta(\nu \Sigma_{f2}) \phi_2], \quad (10)$$

$$\begin{aligned}
(\phi^+ \Delta K \phi') &\approx \int dv_{\text{cell}} [\phi_1^+ \Delta(\Sigma_{a1}) \phi_1 + \phi_2^+ \Delta(\Sigma_{a2}) \phi_2 + \\
&(\phi_1^+ \phi_1 - \phi_2^+ \phi_1) \Delta(\Sigma_{s1}) + j_1^+ \Delta(\frac{1}{D_1}) j_1 + j_2^+ \Delta(\frac{1}{D_2}) j_2], \quad (11)
\end{aligned}$$

$$(\phi^+ H \phi') \approx \int dv_{\text{reactor}} [\phi_1^+ v \Sigma_{f1} \phi_1 + \phi_2^+ v \Sigma_{f2} \phi_2], \quad (12)$$

where $\Delta \Sigma = \Sigma'_{\text{new cell}} - \Sigma_{\text{old cell}}$, dv = volume increment,

$j = -D \nabla \phi = -D' \nabla \phi' = \text{current}$, $j^+ = D \nabla \phi^+ = \text{adjoint current}$,

$$\text{and } \Delta(\frac{1}{D}) = \left(\frac{1}{D'} - \frac{1}{D} \right).$$

Since the perturbation is confined to a single cell, the perturbation integrals can be approximated by the value of the integrand times the cross sectional area of the cell times the contribution from a cell of partial length. Radial symmetry about the axis of the cylinder has been assumed for the flux. A longitudinal cosine distribution has also been assumed. Therefore the flux $\phi(r, z)$ can be approximated by $\phi(r, z) = \phi(r) \phi(z) = \phi(r) \cos K_z z$ where K_z is the square root of the longitudinal buckling. Also $\phi^+(r, z) = \phi^+(r) \cos K_z z$.

Rewriting the products for numerical evaluation, one gets

$$(\phi^+ \Delta K \phi') = \frac{\pi d_{\text{cell}}^2}{4} \int_0^{z_1} \phi_1^+(r) [\Delta(v \Sigma_{f1}) \phi_1(r) + \Delta(v \Sigma_{f2}) \phi_2(r)] \cos^2 K_z z \, dz, \quad (13)$$

$$(\phi^+ H \phi') = 4\pi \int_0^{z_2} \int_{r_1}^{r_2} r \phi_1^+(r) [v \Sigma_{f1} \phi_1(r) + v \Sigma_{f2} \phi_2(r)] \cos^2 K_z z \, dz \, dr, \quad (14)$$

where r_1 = inner radius of reactor

r_2 = outer radius of reactor,

$$\begin{aligned}
(\phi^+ \Delta K \phi) = & \frac{\pi d^2_{\text{cell}}}{4} \left[\int_0^{z_1} [\phi_1^+(r) \Delta(\Sigma_{a1}) \phi_1(r) + \phi_2^+(r) \Delta(\Sigma_{a2}) \phi_2(r) \right. \\
& \left. + \{\phi_1^+(r) \phi_1(r) - \phi_2^+(r) \phi_1(r)\} \Delta(\Sigma_{s1})] \cos^2 K_z z \, dz + \int_0^{z_1} [D_1 \nabla \phi_1^+ \Delta(\frac{1}{D_1}) D_1 \nabla \phi_1 + D_2 \nabla \phi_2^+ \Delta(\frac{1}{D_2}) D_2 \nabla \phi_2] \, dz \right], \quad (15)
\end{aligned}$$

$$\begin{aligned}
\phi^+ \Delta K \phi = & \frac{\pi d^2_{\text{cell}}}{4} \left\{ \int_0^{z_1} \left[\phi_1^+(r) \Delta(\Sigma_{a1}) \phi_1(r) + \phi_2^+(r) \Delta(\Sigma_{a2}) \phi_2(r) + \{\phi_1^+(r) \phi_1(r) - \phi_2^+(r) \phi_1(r)\} \Delta(\Sigma_{s1}) \right] \cos^2 K_z z \, dz \right. \\
& \left. + \int_0^{z_1} \left[D_1 \left(1 - \frac{D_1}{D_1'}\right) \left(\frac{\delta \phi_1^+}{\delta r} \frac{\delta \phi_1}{\delta r} + \frac{\delta \phi_1^+}{\delta z} \frac{\delta \phi_1}{\delta z} \right) + D_2 \left(1 - \frac{D_2}{D_2'}\right) \left(\frac{\delta \phi_2^+}{\delta r} \frac{\delta \phi_2}{\delta r} + \frac{\delta \phi_2^+}{\delta z} \frac{\delta \phi_2}{\delta z} \right) \right] dz \right\} \\
= & \frac{\pi d^2_{\text{cell}}}{4} \left\{ \int_0^{z_1} \left[\phi_1^+(r_i) \Delta(\Sigma_{a1}) \phi_1(r_i) + \phi_2^+(r_i) \Delta(\Sigma_{a2}) \phi_2(r_i) + \{\phi_1^+(r_i) \phi_1(r_i) - \phi_2^+(r_i) \phi_1(r_i)\} \Delta(\Sigma_{s1}) \right] \cos^2 K_z z \, dz \right. \\
& \left. + \int_0^{z_1} \left[D_1 \left(1 - \frac{D_1}{D_1'}\right) \left(\frac{[\phi_1^+(r_i) - \phi_1^+(r_{i-1})]}{[r_i - r_{i-1}]} \frac{[\phi_1(r_i) - \phi_1(r_{i-1})]}{[r_i - r_{i-1}]} \cos^2 K_z z + \phi_1^+(r_i) \phi_1(r_i) \sin^2 K_z z \right) \right. \right. \\
& \left. \left. + D_2 \left(1 - \frac{D_2}{D_2'}\right) \left(\frac{[\phi_2^+(r_i) - \phi_2^+(r_{i-1})]}{[r_i - r_{i-1}]} \frac{[\phi_2(r_i) - \phi_2(r_{i-1})]}{[r_i - r_{i-1}]} \cos^2 K_z z + \phi_2^+(r_i) \phi_2(r_i) \sin^2 K_z z \right) \right] dz \right\}. \quad (16)
\end{aligned}$$

See section 7 for the detailed coding of the problem.

5.1 Input

The necessary input data are the radial lattice points, the normal and adjoint fluxes at each lattice point, the two-group constants for each region, and the dimensions of the reactor.

The fluxes needed as input data can be obtained from the output of radial Program F_2^1 cases. If the flux and current are not strongly affected by the cell replacement, the unperturbed flux may be used. However, if there is a strong perturbation introduced by the cell replacement, the perturbed flux should be used in order to obtain meaningful results. Note: only the unperturbed adjoint flux is involved in the derivation of the perturbation equations.

The two-group constants for each region can be obtained from the Program C_2^2 (bare reactor diffusion theory) used as input for the radial Program F_2 cases. The system multiplication factor, k , must be obtained from a C_2 - F_2 reactivity match. The actual matched value for system multiplication can be obtained by solving simultaneously the linear equation for Program C_2 multiplication as a function of equivalent bare core diameter and the corresponding linear equation obtained from Program F_2 .

See sample input forms.

5.2 Output

The output consists of

- (a) input data,
- (b) cell area,
- (c) calculated reactivities as a function of radius and individual contribution from each process,
- (d) normalization factor,
- (e) value of $(\phi^+ H \phi)$,
- (f) cell area/ $(\phi^+ H \phi)$.

See sample output.

¹ "Nuclear Codes Group Newsletter No. 4", Atomic Energy Commission Computing Facility, Institute of Mathematical Sciences, New York University, June 1, 1957.

² Vollenweider, D. B., "Bare Reactor Program (704 Program C-2)", XDC 57-10-10, July 30, 1957.

5/8/58

1

CELL REMOVAL PROGRAM

Note keypunch: This must be verified.

0 TEST 0 CASE 0 1 03 MARY 0 STANLEY 0 665

71 Spaces of Identification

1	11	21	31	41
② 20	⑨ 2	④ 20.0+0	④ 40.0+0	⑤ 3.0+0
No. of lattice points ≤ 100 .	No. of regions including cell ≤ 11 .	Length of rod withdrawn.	1/2 core length.	One-group extrapolation distance.

Enter in integer form at far right of each field.

1	11
⑤ 2.0+0	⑤ 1.0+0
Cell diameter.	Reactivity, k.

Note: All numerical entries must be in FORTRAN floating point with a field width of 10 unless otherwise specified.

Enter consecutively R_i , ϕ_{1i} , ϕ_{2i} , ϕ_{1i}^+ , ϕ_{2i}^+ for all lattice points i ; e.g. R_1 , R_2 ,

1	11	21	31	41	51	61
⑤ 0.0+0	⑤ 2.0+0	⑤ 4.0+0	⑤ 6.0+0	⑤ 8.0+0	④ 10.0+0	④ 12.0+0
④ 14.0+0	④ 16.0+0	④ 18.0+0	④ 20.0+0	④ 22.0+0	④ 24.0+0	④ 26.0+0
④ 28.0+0	④ 30.0+0	④ 32.0+0	④ 34.0+0	④ 36.0+0	④ 38.0+0	⑤ 1.0+0
④ 0.99+0	④ 0.98+0	④ 0.97+0	④ 0.96+0	④ 0.95+0	④ 0.94+0	④ 0.93+0
④ 0.92+0	④ 0.91+0	④ 0.90+0	④ 0.89+0	④ 0.88+0	④ 0.87+0	④ 0.86+0

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CONTINUATION OF $R_i, \phi_{1i}, \phi_{2i}, \phi_{1i}^+, \phi_{2i}^+$

1	11	21	31	41	51	61
④ 0.85+0	④ 0.84+0	④ 0.83+0	④ 0.82+0	④ 0.81+0	④ 0.05+0	④ 0.05+0
③ 0.051+0	③ 0.051+0	③ 0.052+0	③ 0.052+0	③ 0.053+0	③ 0.053+0	③ 0.054+0
③ 0.054+0	③ 0.055+0	③ 0.055+0	③ 0.056+0	③ 0.057+0	③ 0.058+0	③ 0.059+0
③ 0.060+0	③ 0.061+0	③ 0.062+0	③ 0.063+0	⑤ 1.0+0	④ 0.99+0	④ 0.98+0
④ 0.97+0	④ 0.96+0	④ 0.95+0	④ 0.94+0	④ 0.93+0	④ 0.92+0	④ 0.91+0
④ 0.90+0	④ 0.89+0	④ 0.88+0	④ 0.87+0	④ 0.86+0	④ 0.85+0	④ 0.84+0
④ 0.83+0	④ 0.82+0	④ 0.81+0	⑤ 1.5+0	④ 1.48+0	④ 1.46+0	④ 1.44+0
④ 1.42+0	④ 1.40+0	④ 1.38+0	④ 1.36+0	④ 1.34+0	④ 1.32+0	④ 1.30+0
④ 1.28+0	④ 1.26+0	④ 1.24+0	④ 1.22+0	④ 1.20+0	④ 1.18+0	④ 1.16+0
④ 1.14+0	④ 1.12+0					

1	11	21	31	41	51	61
(3) 1.0E+09	(3) 1.0E+09					
D_1 of cell	D_2 of cell	Σ_{a1} of cell	Σ_{a2} of cell	$v\Sigma_{f1}$ of cell	$v\Sigma_{f2}$ of cell	Σ_{s1} of cell

(4) 10.0 + 0	(5) 2.0 + 0	(5) 0.5 + 0	(2) 5.00E-03	(5) 0.1 + 0	(4) 0.01 + 0	(5) 0.2 + 0
Radial location of cell	D_1	D_2	Σ_{a1}	Σ_{a2}	$v\Sigma_{f1}$	$v\Sigma_{f2}$

(3) 2.3 E-02	(4) 38.0 + 0					
Σ_{s1}	Outer radius of region	D_1	D_2	Σ_{a1}	Σ_{a2}	$v\Sigma_{f1}$

$v\Sigma_{f2}$	Σ_{s1}	Outer radius of region	D_1	D_2	Σ_{a1}	Σ_{a2}

$v\Sigma_{f1}$	$v\Sigma_{f2}$	Σ_{s1}	Outer radius of region	D_1	D_2	Σ_{a1}

Σ_{a2}	$v\Sigma_{f1}$	$v\Sigma_{f2}$	Σ_{s1}	Outer radius of region	D_1	D_2

Σ_{a1}	Σ_{a2}	$v\Sigma_{f1}$	$v\Sigma_{f2}$	Σ_{s1}	Outer radius of region	D_1

D_2	Σ_{a1}	Σ_{a2}	$v\Sigma_{f1}$	$v\Sigma_{f2}$	Σ_{s1}	Outer radius of region

NOTE: Another copy of this page may be used for 4 more regions.

411 013

1CELL REPLACEMENT PROGRAM ANPD REACTOR PHYSICS UNIT

TEST CASE 1 MARY STANLEY 665
020 LATTICE POINTS, 2 REGIONS INCLUDING CFL

CELL DIAMETER= 2.000E 00, INITIAL REACTIVITY= 1.000E 00

DIRECT AND ADJOINT FLUXES

RADIUS	FAST FLUX	SLOW FLUX	FAST ADJOINT	SLOW ADJOINT
0.	1.00000E 00	5.00000E-02	1.00000E-00	1.50000E 00
2.0000E 00	9.90000E-01	5.00000E-02	9.90000E-01	1.48000E 00
4.0000E 00	9.80000E-01	5.10000E-02	9.80000E-01	1.46000E 00
6.0000E 00	9.70000E-01	5.10000E-02	9.70000E-01	1.44000E 00
8.0000E 00	9.60000E-01	5.20000E-02	9.60000E-01	1.42000E 00
1.0000E 01	9.50000E-01	5.20000E-02	9.50000E-01	1.40000E 00
1.2000E 01	9.40000E-01	5.30000E-02	9.40000E-01	1.38000E 00
1.4000E 01	9.30000E-01	5.30000E-02	9.30000E-01	1.36000E 00
1.6000E 01	9.20000E-01	5.40000E-02	9.20000E-01	1.34000E 00
1.8000E 01	9.10000E-01	5.40000E-02	9.10000E-01	1.32000E 00
2.0000E 01	9.00000E-01	5.50000E-02	9.00000E-01	1.30000E 00
2.2000E 01	8.90000E-01	5.50000E-02	8.90000E-01	1.28000E 00
2.4000E 01	8.80000E-01	5.60000E-02	8.80000E-01	1.26000E 00
2.6000E 01	8.70000E-01	5.70000E-02	8.70000E-01	1.24000E 00
2.8000E 01	8.60000E-01	5.80000E-02	8.60000E-01	1.22000E 00
3.0000E 01	8.50000E-01	5.90000E-02	8.50000E-01	1.20000E 00
3.2000E 01	8.40000E-01	6.00000E-02	8.40000E-01	1.18000E 00
3.4000E 01	8.30000E-01	6.10000E-02	8.30000E-01	1.16000E 00
3.6000E 01	8.20000E-01	6.20000E-02	8.20000E-01	1.14000E 00
3.8000E 01	8.10000E-01	6.30000E-02	8.10000E-01	1.12000E 00

OTWO-GROUP CONSTANTS (CELL CONSTANTS ARE LISTED FIRST)

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D1	D2	SIGA1	SIGA2	NU SIGF1	NU SIGF2	SIGS1	OUTER RADIUS
1.0000E 09	1.0000E 09	-0.	-0.	-0.	-0.	-0.	1.0000E 01
2.0000E 00	5.0000E-01	5.0000E-03	10.0000E-02	10.0000E-03	2.0000E-01	3.0000E-03	3.8000E 01

OROD LENGTH=2.0000E 01 1/2 CORE LENGTH=4.0000E 01

OCALCULATED REACTIVITIES

RADIUS	NORMALIZING FACTOR	DELTA K/K LEAKAGE	DELTA K/K ABSORPTION	DELTA K/K SLOWING DOWN	DELTA K/K FISSION	DELTA K/K TOTAL
0.	9.1399E-04	-7.9458E-06	1.9197E-04	-2.3036E-05	-3.0715E-04	-1.4616E-04
2.0000E 00	9.1399E-04	-8.5564E-06	1.8890E-04	-2.2350E-05	-3.0256E-04	-1.4456E-04
4.0000E 00	9.1399E-04	-8.3653E-06	1.8810E-04	-2.1672E-05	-3.0100E-04	-1.4294E-04
6.0000E 00	9.1398E-04	-8.2496E-06	1.8503E-04	-2.1004E-05	-2.9644E-04	-1.4066E-04
8.0000E 00	9.1398E-04	-8.0615E-06	1.8416E-04	-2.0345E-05	-2.9486E-04	-1.3910E-04
1.0000E 01	9.1398E-04	-7.9488E-06	1.8110E-04	-1.9696E-05	-2.9033E-04	-1.3687E-04
1.2000E 01	9.1398E-04	-7.7637E-06	1.8017E-04	-1.9055E-05	-2.8872E-04	-1.3536E-04
1.4000E 01	9.1398E-04	-7.6541E-06	1.7711E-04	-1.8424E-05	-2.8422E-04	-1.3319E-04
1.6000E 01	9.1398E-04	-7.4720E-06	1.7612E-04	-1.7802E-05	-2.8257E-04	-1.3173E-04
1.8000E 01	9.1398E-04	-7.3656E-06	1.7305E-04	-1.7189E-05	-2.7810E-04	-1.2961E-04
2.0000E 01	9.1398E-04	-7.1864E-06	1.7200E-04	-1.6586E-05	-2.7643E-04	-1.2820E-04
2.2000E 01	9.1397E-04	-7.0830E-06	1.6894E-04	-1.5991E-05	-2.7199E-04	-1.2613E-04
2.4000E 01	9.1397E-04	-6.9069E-06	1.6782E-04	-1.5406E-05	-2.7029E-04	-1.2478E-04
2.6000E 01	9.1397E-04	-6.7706E-06	1.6666E-04	-1.4830E-05	-2.6855E-04	-1.2349E-04
2.8000E 01	9.1397E-04	-6.6359E-06	1.6546E-04	-1.4264E-05	-2.6678E-04	-1.2223E-04
3.0000E 01	9.1397E-04	-6.5026E-06	1.6421E-04	-1.3706E-05	-2.6499E-04	-1.2099E-04
3.2000E 01	9.1397E-04	-6.3708E-06	1.6291E-04	-1.3158E-05	-2.6316E-04	-1.1978E-04
3.4000E 01	9.1397E-04	-6.2404E-06	1.6156E-04	-1.2619E-05	-2.6130E-04	-1.1860E-04
3.6000E 01	9.1397E-04	-6.1116E-06	1.6017E-04	-1.2089E-05	-2.5941E-04	-1.1744E-04
3.8000E 01	9.1397E-04	-5.9842E-06	1.5874E-04	-1.1568E-05	-2.5749E-04	-1.1631E-04

Q(APHI,H,PHI)=3.4378E 03, CELL AREA=3.1416E 00, V/H=9.1384E-04
 OEND OF CASE

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5.3 Operating Procedure

The program is completely self contained in the binary deck. It requires the lower $(4452)_8$ locations and the upper $(3177)_8$ locations of core storage. Thus the program may be run on a 704 of any size since it requires only the minimum memory, no drums and 1 or 2 tapes. All output is on tape 3. If sense switch 2 is down, load data on cards. If more than one case is to be run, stack the cases behind the binary deck. Press start after each stop at $(1522)_8$ to run successive cases. If sense switch 2 is up, load data from input tape 2.

The machine time per case is approximately two minutes.

Program DELTA has not been put on either the POP or OPERA tape.

6. SUMMARY

The Cell Removal Program should prove useful for calculating the worth of small perturbations and for calculating radial and longitudinal importance functions. The accuracy of $\Delta k/k$ is dependent upon the degree to which the unperturbed fluxes given as input are a good approximation for the perturbed fluxes. This is a limitation of first order perturbation theory.

7. LISTING OF SOURCE PROGRAM

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C      CELL REMOVAL PROGRAM, DELTA  ANPD  MARY STANLEY
C      OPERATING INSTRUCTIONS--INPUT ON CARDS,OUTPUT ON TAPE 3.
C      PRINT OUTPUT ON PROGRAM CONTROL, 120 CHARACTERS PER LINE.
C      TO RUN SEVERAL CASES, STACK INPUT DATA IN SEQUENCE AND PRESS START
C      1 BUTTON AFTER EACH STOP AT OCTAL 77777.
      DIMENSION R(100),PHI1(100),PHI2(100),APHI1(100),APHI2(100),C(8,11)
      1,RD(100),Y(100),D(100),A(100),F(100),S(100),DKT(100),X(100),DELR(1
      200)
10     FORMAT(55H1CELL REPLACEMENT PROGRAM  ANPD  REACTOR PHYSICS UNIT/
      1/)
12     FORMAT(72H0
      1
      )
14     FORMAT(2I10,3E10.3)
16     FORMAT(7E10.3)
18     FORMAT(1H012,16H LATTICE POINTS,13,23H REGIONS INCLUDING CELL//15H
      1 CELL DIAMETER=1PE10.3,21H, INITIAL REACTIVITY=1PE10.3///26H DIREC
      2T AND ADJOINT FLUXES//73H RADIUS          FAST FLUX          SLOW FLUX
      3 FAST ADJOINT SLOW ADJOINT//)
20     FORMAT(1H 1PE10.4,1P4E15.5)
22     FORMAT(//55H0TWO-GROUP CONSTANTS (CELL CONSTANTS ARE LISTED FIRST)
      1 //120H D1          D2          SIGA1          SIGA2
      2 NU SIGF1          NU SIGF2          SIGS1          OUTER RADIUS  //)
24     FORMAT(1H 1PE10.4,1P7E15.4)
28     FORMAT(//24H0CALCULATED REACTIVITIES//106H RADIUS          NORMALIZ
      1ING DELTA K/K          DELTA K/K          DELTA K/K          DELTA K/K
      2 DELTA K/K          /106H          FACTOR          LEAKAGE
      3 ABSORPTION          SLOWING DOWN          FISSION          TOTAL          //)
30     FORMAT(1H 1PE10.4,1P6E15.4)
32     FORMAT(14H0(APHI,H,PHI)=1PE10.4,12H, CELL AREA=1PE10.4,6H, V/H=1PE
      110.4)
33     FORMAT(12H0ROD LENGTH=1PE10.4,17H 1/2 CORE LENGTH=1PE10.4//)
34     FORMAT(12H0END OF CASE)
C      READ AND PRINT INPUT DATA
      IF(SENSE SWITCH 2) 100,4
100    READ 12
105    READ 14,N,M,Z1,Z2,DEE
110    READ 16,DCELL,REAC
115    READ 16,(R(I),I=1,N),(PHI1(I),I=1,N),(PHI2(I),I=1,N),(APHI1(I),I=1
      1,N),(APHI2(I),I=1,N)
120    READ 16,((C(I,J),I=1,8)J=1,M)
      GO TO 125
400    READ INPUT TAPE 2,12
      READ INPUT TAPE 2,14,N,M,Z1,Z2,DEE
      READ INPUT TAPE 2,16,DCELL,REAC
      READ INPUT TAPE 2,16,(R(I),I=1,N),(PHI1(I),I=1,N),(PHI2(I),I=1,N),
      1(APHI1(I),I=1,N),(APHI2(I),I=1,N)
      READ INPUT TAPE 2,16,((C(I,J),I=1,8),J=1,M)
125    WRITE OUTPUT TAPE3,10
130    WRITE OUTPUT TAPE3,12
135    WRITE OUTPUT TAPE3,18,N,M,DCELL,REAC
140    WRITE OUTPUT TAPE3,20,(R(I),PHI1(I),PHI2(I),APHI1(I),APHI2(I),I=1,
      1N)
145    WRITE OUTPUT TAPE3,22
150    WRITE OUTPUT TAPE3,24,((C(I,J),I=1,8),J=1,M)
155    WRITE OUTPUT TAPE3,33,Z1,Z2
C      CALCULATE INTEGRANDS Y,D,A,F AND S

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160 J=2
165 DO 200 I=1,N
170 IF(R(I)-C(8,J))180,180,175
175 J=J+1
180 Y(I)=APHI1(I)*(C(5,J)*PHI1(I)+C(6,J)*PHI2(I))
185 A(I)=APHI1(I)*(C(3,1)-C(3,J))*PHI1(I)+APHI2(I)*(C(4,1)-C(4,J))*PHI
12(I)
190 F(I)=APHI1(I)*(C(5,1)-C(5,J))*PHI1(I)+APHI1(I)*(C(6,1)-C(6,J))*PHI
12(I)
195 S(I)=(APHI1(I)*PHI1(I)-APHI2(I)*PHI1(I))*(C(7,1)-C(7,J))
200 CONTINUE
205 ARGC=2.*(Z2+DEE)
210 AX=(3.14159/ARGC)**2*(Z1/2.0-(ARGC/12.56636)*SINF(6.28318*Z1/ARGC)
1)
215 E=Z1/2.+(ARGC/12.56636)*SINF(6.28318*Z1/ARGC)
220 CX=Z2/2.+(ARGC/12.56636)*SINF(6.28318*Z2/ARGC)
225 J=2
230 D(1)=C(1,J)*(1.0-C(1,J)/C(1,1))*APHI1(1)*PHI1(1)*AX+C(2,J)*(1.0-C(
12,J)/C(2,1))*APHI2(1)*PHI2(1)*AX
235 DO260I=2,N
236 DELR(I)=(R(I)-R(I-1))*2
240 IF(R(I)-C(8,J))250,250,245
245 J=J+1
250 D(I)=C(1,J)*(1.0-C(1,J)/C(1,1))*((APHI1(I)-APHI1(I-1))*(PHI1(I)-PH
1I1(I-1))*E/DELR(I)+APHI1(I)*PHI1(I)*AX)+C(2,J)*(1.0-C(2,J)/C(2,1))
2*((APHI2(I)-APHI2(I-1))*(PHI2(I)-PHI2(I-1))*E/DELR(I)+APHI2(I)*PHI
32(I)*AX)
260 CONTINUE
C CALCULATE INTEGRALS
265 DO 270 I=1,N
270 X(I)=Y(I)*R(I)
275 H=0.
280 DO 285 I=2,N
285 H=H+(X(I)+X(I-1))*(R(I)-R(I-1))
290 H=6.28318*H*CX
295 V=3.14159*(DCELL**2)/4.0
300 B=V/H
305 DO340I=1,N
310 RD(I)=B/(1.0+REAC*B*((A(I)+S(I))*E+D(I)))
315 D(I)=-REAC*RD(I)*D(I)
320 A(I)=-REAC*RD(I)*A(I)*E
325 S(I)=-REAC*RD(I)*S(I)*E
330 F(I)=RD(I)*F(I)*E
335 DKT(I)=D(I)+A(I)+S(I)+F(I)
340 CONTINUE
C PRINT OUTPUT
345 WRITE OUTPUT TAPE3,28
350 WRITE OUTPUT TAPE3,30,(R(I),RD(I),D(I),A(I),S(I),F(I),DKT(I),I=1,N
1)
360 WRITE OUTPUT TAPE3,32,H,V,B
365 WRITE OUTPUT TAPE3,34
370 END FILE 3
375 PAUSE 77777
380 GO TO 100

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