192
3-18-80

DR 886

MASTER

HEDL-TME 79-72
UC-79h

**DILATE — A 2-D STRUCTURAL
PROGRAM FOR THE DILATION
RESPONSE OF HEXAGONAL DUCTS**

Hanford Engineering Development Laboratory

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
P.O. Box 1970 Richland, WA 99352
A Subsidiary of Westinghouse Electric Corporation
Prepared for the U.S. Department of Energy
under Contract No. DE-AC14-76FF02170

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the U.S. DOE, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy A11 ; Microfiche \$2.25

DILATE — A 2-D STRUCTURAL PROGRAM FOR THE DILATION RESPONSE OF HEXAGONAL DUCTS

Hanford Engineering Development Laboratory

D.P. Chan

February 1980

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
P.O. Box 1970 Richland, WA 99352
A Subsidiary of Westinghouse Electric Corporation
Prepared for the U.S. Department of Energy
under Contract No. DE-AC14-76FF02170.

DILATE
A 2-D STRUCTURAL PROGRAM FOR THE
DILATION RESPONSE OF HEXAGONAL DUCTS

D. P. Chan

ABSTRACT

An analytical method is introduced for determining the dilation of hexagonal ducts in fast reactors. The method, which is valid for temperatures where creep is linearly dependent on stress, was implemented in a fast-running computer called DILATE. A bench-mark program is presented, which shows the results of the DILATE program in close agreement with the results of the finite element program MARC-CDC. User instructions for the DILATE program are described in detail and a listing of the program is included.

ACKNOWLEDGEMENTS

The author gratefully acknowledges financial sponsorship by the Fuel Systems Branch of the U.S. Department of Energy (DOE) and the general guidance and direction under W. E. Roake, C. M. Cox and D. S. Dutt of the Hanford Engineering Development Laboratory (HEDL) Fuels and Controls Department. Special thanks are due to R. J. Jackson, the author's manager from 1976 to 1979, whose sincere concern and constant encouragement for the fuel assembly work were inspirational in the development of the analytical method presented in this report.

CONTENTS

	<u>Page</u>
Abstract	iii
Acknowledgements	iv
Figures	vi
Nomenclature	vii
I. SUMMARY	1
II. INTRODUCTION	3
III. THEORY	5
IV. BENCH-MARK PROBLEM	13
V. INPUT INSTRUCTIONS	21
VI. PROGRAM OUTPUT	27
VII. REFERENCES	29
APPENDIX A ELEMENTS OF MATRICES A & B	A-1
APPENDIX B LISTING OF THE DILATE PROGRAM	B-1

FIGURES

<u>Figure</u>	<u>Page</u>
1 FTR Fuel Assembly	4
2 Hexagonal Duct Under the Influence of Temperature, Pressure and Fast Neutron Flux	6
3 Mathematical Model of the Hexagonal Duct	7
4 Determination of the Axial Load	11
5 Comparison of Duct Dilation Calculations	15
6 Bending Stress Along the Inside Surface of the Duct Wall	16
7 Creep Along the Inside Surface of the Duct Wall	17
8 Finite Element Model of the Hex Duct	18

TABLES

<u>Table</u>	<u>Page</u>
1 Dilation Response of D68 Hex Duct	28

NOMENCLATURE

- A - Cross sectional area (in.²)
- E - Young's modulus (psi)
- F - Axial force (lb)
- h - Thickness of duct (in.)
- I - Section modulus (in.⁴)
- L - Half of corner to corner distance along flat surface (in.)
- M - Bending moment (lb-in.)
- n - Subscript denotes the quantity at time step (n)
- p - Internal pressure (psi)
- T - Uniform temperature (°F)
- t - Time (hr)
- u - Displacement in X direction (in.), Figure 3
- V - Shear force (lb)
- v - Displacement in Y direction (in.), Figure 8
- w - Displacement in Z direction (in.), Figure 3
- X,Z - Coordinate directions in beam model, Figure 8
- X,Y - Coordinate directions in finite element model, Figure 8
- x - Distance along duct wall (in.)
- z - Distance along duct mid-wall (in.)
- ϕ - Fast neutron flux (n/cm²-sec, E > 0.1 MeV)
- α - Coefficient of thermal expansion (/°F)
- ϵ - Total strain
- $\Delta\epsilon^S$ - Irradiation swelling strain increment
- $\Delta\epsilon^C$ - Irradiation creep strain increment
- σ - Axial stress (psi)

DILATE
A 2-D STRUCTURAL PROGRAM FOR THE
DILATION RESPONSE OF HEXAGONAL DUCTS (FF064)

I. SUMMARY

To ascertain that a fast reactor fuel assembly duct will meet its design life, one of the technical issues to be examined is the duct-to-duct touching due to duct dilations. With the availability of finite element computer programs, the duct dilation problem can be easily analyzed. The number of cases to be examined for different combinations of loading conditions is very large because of the variation of pressure, temperature and fast neutron flux throughout the FFTF core. It is desirable to have a fast analytical method as an alternative to the finite element method. In the following an analytic method is introduced that can easily calculate the stress, strain and deflection of the duct wall as a function of irradiation history for temperatures $\sim 900^{\circ}\text{F}$ (755K) where creep is linearly dependent on stress. Solutions are carried out for a duct with constant pressure differential. Results are in close agreement with finite element results of the MARC-CDC program.⁽²⁾ The computer running time for the method is one or two orders of magnitude less than that for the finite element program. User instructions for the DILATE program are described in detail. A listing of the program is included.

II. INTRODUCTION

In the Fast Flux Test Facility (FFTF) core, there are 73 driver fuel assemblies. Each assembly is basically an hexagonal component (see Figure 1). It consists of an inlet nozzle, shield-orifice assembly, duct, load pads, handling socket and fuel pin bundle. The inlet nozzle rests on the core support structure. Coolant enters the assembly through the six slots in the inlet nozzle. The shield orifice assembly provides control of coolant flow rate and prevents neutron streaming. The load pads provide lateral support to the fuel assembly, transferring the loads developed to the radial restraint system. The handling socket mates with the In-Vessel Handling Machine grapple during refueling operations and guides coolant into the Instrument Tree during reactor operation.

The principal structural members of the fuel assembly are the fuel pin bundle and the duct tube. Most assemblies are designed to operate in the FFTF core for 300 full power days. To ascertain that the duct tube will meet its design life, several technical issues have to be examined, including the dilation of the duct under pressure, temperature and fast neutron fluence. The duct wall must be thick enough so that 1) there is not enough dilation of the ducts to cause duct-to-duct touching and 2) there is not enough accumulated total inelastic strain in the duct to cause duct failure. Conversely, the ducts must be as thin as practical to reduce the core's amount of metal, which captures neutrons and thus impairs the breeding performance of the reactor.

HEDL 7806-207.14

FIGURE 1. FTR Fuel Assembly. Neg 7808025-1

III. THEORY

Figure 2 shows the cross-sectional view of a hexagonal duct under the influence of pressure, temperature and fast neutron flux at time t_n . Assuming symmetry conditions in geometry and loading, the mathematical model of a unit depth of the duct can be reduced to that shown in Figure 3. The basic equations are:

Equilibrium

$$p_n = \frac{dV_n}{dx} \quad (1)$$

$$V_n = \frac{dM_n}{dx} - F_n \frac{dw_n}{dx} \quad (2)$$

Compatibility

$$\epsilon_n = -z \frac{d^2 w_n}{dx^2} + \frac{du_n}{dx} \quad (3)$$

Stress-Strain

$$\epsilon_n = \frac{\sigma_n}{E} + \alpha T_n + \sum_{i=0}^{n-1} \Delta \epsilon_i^S + \sum_{i=0}^{n-1} \Delta \epsilon_i^C \quad (4)$$

where:

$$\Delta \epsilon_i^C = \sigma_i K_i \quad (5)$$

and

K_i and $\Delta \epsilon_i^S$ are functions of the fast neutron flux, time and temperature.

HEDL 7806-207.12

FIGURE 2. Hexagonal Duct Under the Influence of Temperature, Pressure and Fast Neutron Flux. Neg 7808025-14

HEDL 7806-207.7

FIGURE 3. Mathematical Model of the Hexagonal Duct. Neg 7808025-7

By substituting Equation (3) into Equation (4), multiplying both sides of the resulting equation by the distance from the mid-wall and integrating over the area of a unit deep duct wall, the following equation is obtained:

$$M_n = E \left[-I \frac{d^2 w_n}{dx^2} - \sum_{i=0}^{n-1} K_i M_i \right] \quad (6)$$

The bending moment is fairly constant with time for the case of constant internal pressure⁽¹⁾. Assuming that the moment is constant, Equation (6) reduces to:

$$M_n = \frac{-I}{\frac{1}{E} + \sum_{i=0}^{n-1} K_i} \frac{d^2 w_n}{dx^2} \quad (7)$$

By substituting Equation (7) into Equation (2), the shear at any time can be expressed as:

$$V_n = \frac{-I}{\frac{1}{E} + \sum_{i=0}^{n-1} K_i} \frac{d^3 w_n}{dx^2} - F_n \frac{dw_n}{dx} \quad (8)$$

From Equations (1) and (8), the governing equation of the duct dilation problem is:

$$p_n = \frac{-I}{\frac{1}{E} + \sum_{i=0}^{n-1} K_i} \frac{d^4 w_n}{dx^4} - F_n \frac{d^2 w_n}{dx^2} \quad (9)$$

The associated boundary conditions are

$$\frac{dw_n}{dx}(0) = 0 \quad (10)$$

$$V_n(0) = 0 \quad (11)$$

$$\frac{dw_n}{dx}(L) = 0 \quad (12)$$

$$\cos 30^\circ u_n(L) + \sin 30^\circ w_n(L) = 0 \quad (13)$$

Equations (10) and (12) state that the slopes are zero at the end points. Equation (11) states that the shear is zero in the middle of the duct flat. Equation (13) states that the displacement in the z' direction (Figure 3) is zero. All four equations are based on symmetry of the boundary conditions.

The solution to Equation (9) for constant p_n is:

$$w_n = C_1^n x + C_2^n + C_3^n e^{\gamma_1^n x} + C_4^n e^{\gamma_2^n x} - \frac{p_n}{2F_n} x^2. \quad (14)$$

where the first four terms on the right-hand-side constitute the homogeneous solution, and the last term is the particular solution. The roots of the homogenous solution are:

$$\gamma_1^n = \sqrt{\frac{-F_n}{I} \left(\frac{1}{E} + \sum_{i=0}^{n-1} K_i \right)}, \quad \gamma_2^n = -\gamma_1^n \quad (15)$$

On the basis of equilibrium for the duct wall (Figure 4), it can be shown that $F_n = -2 \cos 30^\circ L p_n$. The displacement along the duct wall is $u = \epsilon_n^0 x$ where ϵ_n^0 is the total strain along the middle surface of the duct wall.

$$u = \left[\frac{F_n}{hE} + \alpha T_n + \sum_{i=0}^{n-1} \Delta \epsilon_i^S + \sum_{i=0}^{n-1} \Delta \epsilon_i^C \right] x \quad (16)$$

The solution w_n is left with four undetermined parameters, C_1^n , C_2^n , C_3^n and C_4^n . There are four boundary conditions available, namely, equations (10), (11), (12) and (13). Substituting w_n into the boundary conditions yields a system of simultaneous algebraic equations,

$$[A] \bar{X} = [B] \quad (17)$$

where $\bar{X} = [C_1^n, C_2^n, C_3^n, C_4^n]$ and the elements of matrices $[A]$ and $[B]$ are shown in Appendix A.

With w_n known, shear can be determined from Equation (8) and moment from Equation (7). Stress and strain can be determined as follows:

$$\begin{aligned} \sigma &= \frac{F_n}{h} + \frac{6M_n}{h^2} \\ \epsilon^S &= \sum_{i=0}^{n-1} \Delta \epsilon_i^S \\ \epsilon^C &= \sum_{i=0}^{n-1} \left(\frac{F_i}{h} + \frac{6M_n}{h^2} \right) K_i \end{aligned} \quad (18)$$

$$\begin{aligned}
 F'_n \sin 30^\circ &= p_n L \\
 F_n &= -F'_n \cos 30^\circ \\
 &= -2 p_n L \cos 30^\circ
 \end{aligned}$$

HEDL 7806-207.1

FIGURE 4. Determination of the Axial Load. Neg 7808025-15

A computer program DILATE was written incorporating Equations 14 through 18. Total irradiation is divided into time steps. Assuming constant temperature, pressure and fast neutron flux, the program calculates stress, strain, deflection, shear, moment and force at each time step.

IV. BENCH-MARK PROBLEM

The DILATE program was used to determine the dilation response of the FFTF reference duct under constant pressure. In row one at the midplane of the FFTF core, the following conditions exist on the duct wall during steady state operation at a nominal coolant inlet temperature of 680°F:

- 1) temperature of 875°F
- 2) pressure differential of 32 psi radially outward
- 3) neutron flux of 4.5×10^{15} n/cm²-sec (E > 0.1 MeV)

The duct tube is 0.120 inch in thickness and 4.575 inches across outside flats. The material is 316 stainless steel with 20% cold work. Thermal creep can be neglected at 875°F.

The irradiation creep law used in the analysis is as follows:

$$\frac{\epsilon}{\tau} = A \left(1 - \epsilon \frac{-\phi t}{\tau_{tr}} \right) + \phi t \bar{B}(\phi t, T)$$

$$\bar{B}(\phi t, T) = F(T) G'(\phi t) + B$$

$$F(T) = \frac{7.2 \times 10^{-25} \epsilon^{\frac{-16000}{RT}}}{1 + 2 \times 10^{19} \epsilon^{\frac{-80000}{RT}}}$$

$$G'(\phi t) = 1 - \frac{\tau}{\phi t} \left(1 - \epsilon \frac{-\phi t}{\tau} \right)$$

$$B = 3 \times 10^{-30} \text{ cm}^2/\text{n} - \text{psi}$$

$$\tau = 7 \times 10^{22} \text{ n/cm}^2$$

$$A = 8.4 \times 10^{-9} / \text{psi}$$

$$\tau_{tr} = 0.043 \times 10^{22} \text{ n/cm}^2$$

$$R = 1.987$$

$$T = {}^{\circ}\text{K}$$

$$\phi = \text{neutron flux, n/cm}^2\text{-sec (E > 0.1 MeV)}$$

$$\phi t = \text{neutron fluence, n/cm}^2 \text{ (E > 0.1 MeV)}$$

The irradiation swelling law used in the analysis is from Reference 3.

Figure 5 describes the dilations of the duct wall at the beginning-of-life and at the end of 3 operating cycles (7200 hr). The maximum dilation occurs at mid-flat, and the minimum, at the corner. At the end-of-irradiation, the duct wall is under constant temperature and pressure, but with the addition of fast neutron fluence. The difference in the dilation curves at the beginning-of-life and at the end-of-irradiation corresponds to the permanent deformation in the duct wall when it is depressurized and brought to room temperature following irradiation.

Figure 6 describes the bending stress along the inside surface of the duct wall at the beginning-of-life and at the end-of-irradiation. The bending stress is compressive at the mid-flat, and tensile at the corner. Maximum stress occurs at the corner.

Figure 7 describes the accumulated creep strain along the inside surface of the duct wall at the end-of-irradiation. Accumulated creep strain is maximum at the duct corner because of the high bending stress.

To check the accuracy of the DILATE results, a finite element model of the duct wall was established (see Figure 8). Three two-dimensional isoparametric curved beam elements of the MARC-CDC program were used. There are a total of 4 nodes each with 4 degrees of freedom (u , v , du/ds , dv/ds where s is the distance along the beam). Symmetry boundary conditions were imposed at node 1 ($v=0$, $du/ds = 0$). Coordinate transformation from the (X,Y) system to the (X',Y') system and tying between degrees of freedom

HEDL 7806-207.11

FIGURE 5. Comparison of Duct Dilation Calculations. Neg 7808025-13

HEDL 7806-207.2

FIGURE 6. Bending Stress Along the Inside Surface of the Duct Wall. Neg 7808025-3

HEDL 7806-207.8

FIGURE 7. Creep Along the Inside Surface of the Duct Wall. Neg 7808025-4

HEDL 7806-207.13

FIGURE 8. Finite Element Model of the Hex Duct. Neg 7808025-13

$(du'/ds = \tan 30^\circ dv'/ds)$ were applied at node 4 to bring about proper boundary conditions. The large displacement option was used. Dilation, stress and strain predictions are shown as dotted curves in Figures 5, 6 and 7. The dotted curves compare favorably to the solid curves obtained from the DILATE program.

The results by the DILATE program were obtained with 0.1 second computation time on a CDC 6600 computer. The results by the MARC-CDC program were obtained with 17 seconds computation time on a CDC 7600 computer.

V. INPUT INSTRUCTIONS

The DILATE program consists of a main program and three subroutines, SOLVEQ, CREEP and SWELL. The following is a typical run stream on CDC 6600 of Boeing Computer Services, Richland, WA:

```
DUCT, DAVE, ADDRESS, PHONE
ACCOUNT (PW=WDC800, UN=WDC800)
FTN.
LGØ.
7/8/9
```

MAIN PROGRAM	}	SOURCE DECK
SUBROUTINE SOLVEQ		
SUBROUTINE CREEP		
SUBROUTINE SWELL		

```
7/8/9
DATA DECK
6/7/8/9
```

The main program has incorporated in its content 316 SS 20% CW material properties corresponding to Nuclear Systems Materials Handbook Revision 3 irradiation creep and Revision 5 irradiation swelling. Advanced alloy properties are incorporated in the main program by the following form:

$$\epsilon = \bar{B} \sigma \phi t \quad (\text{irradiation creep strain}) \quad (19)$$

$$\bar{B} = (A + B t) F(T)/P$$

$$F(T) = \left[J + K \left(\frac{T-400}{350} \right) + 10^{-29} L e^{(C-DT)} + \frac{Ee \frac{-Q_1}{RT}}{1 + Fe \frac{-Q_2}{RT}} + Ge \frac{-Q_3}{RT} \right] \times 10^{29}$$

where:

ϵ = effective creep strain
 σ = effective stress (MPa)
 t = neutron fluence (n/cm^2 , $E > 0.1$ MeV)
 T = temperature (K)
 R = gas constant (1.987 cal/mole/K)

$$\epsilon = 1/3 (S_0 - D) \quad (\text{irradiation swelling strain}) \quad (20)$$

$$S_0 = \dot{S}_0 \left[\phi t + \frac{1}{\alpha} \ln \frac{1 + e^{\alpha(\tau - \phi t)}}{1 + e^{\alpha \tau}} \right]$$

$$D = D^* \left[1 - e^{-\lambda \phi t} \right]$$

$$\dot{S}_0 = A_1 e^{-b_1 (T - T_{p1})^2} + A_2 e^{-b_2 (T - T_{p2})^2}$$

where:

ϕt = neutron fluence ($E > 0.1$ MeV, $10^{22} n/cm^2$)
 $\alpha = 0.75$
 T = temperature (K)

The program user may use the built-in 316 SS 20% CW or advanced alloy material properties for the hex duct by supplying the necessary material constants in the data deck. In that case, the subroutines CREEP and SWELL may be deleted from the run stream. The program user may also use any material for the hex duct by programming his own subroutines CREEP and SWELL. Appendix B has listings of SUBROUTINES CREEP and SWELL corresponding to NSMH Revision 3 creep and Revision 5 swelling for 316 SS 20% CW respectively. The parameters in the subroutines CREEP and SWELL are as follows:

STRESS = stress (psi)
 TEMPK = temperature (K)
 FLU = fast neutron fluence (n/cm^2)
 ECRM = irradiation creep strain
 ESW = irradiation swelling strain

After accepting stress, temperature and fast neutron fluence from the main program, the subroutines calculate and return creep and swelling strains.

The data deck should be as follows:

<u>Columns</u>	<u>Format</u>	<u>Entry</u>
1st Card		
1-80	10A8	Title
2nd Card		
1-10	F10	Thickness (in.)
11-20	F10	Half width (in.)
21-30	F10	Young's modulus (psi)
31-40	F10	Coefficient of thermal expansion ($/^{\circ}F$)
45-50	I5	Number of stations along duct wall
55-60	I5	Material flag
		1 - 316 SS 20% CW
		2 - advanced alloy
		3 - user input subroutines CREEP and SWELL
65-70	I5	Number of time steps

<u>Columns</u>	<u>Format</u>	<u>Entry</u>
3rd Card		
1-10	F10	Non-dimensionalized distance of the first station from the middle of the duct flat 0 - middle of duct flat 1 - duct corner
11-20	F10	2nd station
21-30	F10	3rd station . . .
4th Card		
1-10	F10	Pressure (psi)
11-20	F10	Temperature (F)
21-30	F10	Fast neutron flux ($E > 0.1$ MeV, n/cm^2 -hr)
31-40	F10	Total time (hr)

Cards 5 and 6 are creep constants for advanced alloy.

5th Card (input only if material flag = 2)

1-10	F10	J
11-20	F10	K
21-30	F10	L
31-40	F10	A
41-50	F10	B
51-60	F10	P
61-70	F10	C

<u>Columns</u>	<u>Format</u>	<u>Entry</u>
----------------	---------------	--------------

6th Card (input only if material flag = 2)

1-10	F10	E
11-20	F10	F
21-30	F10	G
31-40	F10	Q_1
41-50	F10	Q_2
51-60	F10	Q_3
71-80	F10	D

Cards 7 and 8 are swelling constants for advanced alloy.

7th Card (input only if material flag = 2)

1-10	F10	Tp_1
11-20	F10	Tp_2
21-30	F10	A_1
31-40	F10	A_2
41-50	F10	b_1
51-60	F10	b_2
61-70	F10	τ
71-80	F10	D^*

8th Card (input only if material flag = 2)

1-10	F10	λ
------	-----	-----------

VI. PROGRAM OUTPUT

The following table shows the typical output from the DILATE program. Input values are printed first followed by calculated values of stress, strain, etc. at different times. Since the theory assumes symmetry in loading and geometry, calculated values along only one-half of the duct flat are printed. The coordinate system and the sign convention for shear, moment and force are shown in Figure 3. The bending stress and the total stress outputs are for the inside surface of the duct wall. The headings and units in the output are self-explanatory.

28

CREEP CONSTANTS, J, K, L, A, T ₀ , D ₀ , C, D ₁ , F ₀ , G, Q ₁ , Q ₂ , Q ₃ , ARE				
0.	0.	0.	.15000E+07	.12000E+50
.50000E+03	.15000E+12	.10000E+17	0.	.33200E+01
SWELLING CONSTANT, T ₀ ¹ , T ₀ ² , A ₁ , A ₂ , A ₃ , Q ₂ , T ₀ ³ , L, ARE			.66000E+05	0.
.75000E+03	0.	.23000E+00	0.	.10000E+02
.30000E+00	.60000E+00		.00000E+04	0.

DISTANCE X IN.	MEMBRANE STRESS PSI	BENDING STRESS PSI	TOTAL STRESS PSI	THERMAL STRAIN -----	SWELLING STRAIN	CRIP STRAIN	DEFLECTION IN.	SHEAR LR.	MOMENT LR-IN	FORCE LB.
0.	.59398E+03	-.76614E+04	-.70674E+04	.72625E-02	0.	0.	-.17115E-01	.39194E-26	-.87873E+01	-.71277E+02
.21434E+00	.59398E+03	-.75567E+04	-.70577E+04	.72625E-02	0.	0.	-.17060E-01	.68588E+01	-.80961E+01	-.71277E+02
.42866E+00	.59398E+03	-.74425E+04	-.70486E+04	.72625E-02	0.	0.	-.16907E-01	.13717E+02	-.58621E+01	-.71277E+02
.64300E+00	.59398E+03	-.73279E+04	-.70394E+04	.72625E-02	0.	0.	-.16682E-01	.20576E+02	-.22070E+01	-.71277E+02
.85734E+00	.59398E+03	-.72185E+04	-.70305E+04	.72625E-02	0.	0.	-.16430E-01	.27435E+02	.29243E+01	-.71277E+02
.10717E+01	.59398E+03	-.70684E+04	-.70225E+04	.72625E-02	0.	0.	-.16217E-01	.34293E+02	.95241E+01	-.71277E+02
.12377E+01	.59398E+03	-.69218E+04	-.70158E+04	.72625E-02	0.	0.	-.16170E-01	.39606E+02	.15652E+02	-.71277E+02
.12860E+01	.59398E+03	-.77745E+04	-.79285E+04	.72625E-02	0.	0.	-.16125E-01	.41152E+02	.17603E+02	-.71277E+02

4Neg 791134-7

VII. REFERENCES

1. D. P. Chan and R. J. Jackson, "An Analytical Study of the Dilation of Fast Reactor Fuel Assembly Ducts," in Proceedings of the Fifth Inter-Conference on Structural Mechanics on Reactor Technology, Berlin, Germany, August 1979.
2. "MARC-CDC Nonlinear Finite Element Analysis Program," Rev. G, Control Data Corp., Minneapolis, MN, 1975.
3. John F. Bates, An Empirical Relationship for Swelling in 20% Cold Worked Stainless Steel, HEDL-TME 76-96, Hanford Engineering Development Laboratory, Richland, WA, March 1977.

APPENDIX A
ELEMENTS OF MATRICES A AND B

APPENDIX A
ELEMENTS OF MATRICES A AND B

$$a_{11} = 1$$

$$a_{12} = 0$$

$$a_{13} = \gamma_1^n$$

$$a_{14} = \gamma_2^n$$

$$a_{21} = 1$$

$$a_{22} = 0$$

$$a_{23} = \gamma_1^n e^{\gamma_1^n L}$$

$$a_{24} = \gamma_2^n e^{\gamma_2^n L}$$

$$a_{31} = F_n$$

$$a_{32} = 0$$

$$a_{33} = F_n \gamma_1^n + \frac{I(\gamma_1^n)^3}{\frac{1}{E} + \sum_{i=0}^{n-1} K_i}$$

$$a_{34} = F_n \gamma_2^n + \frac{I(\gamma_2^n)^3}{\frac{1}{E} + \sum_{i=0}^{n-1} K_i}$$

$$a_{41} = -\frac{L}{2}$$

$$a_{42} = -\frac{1}{2}$$

$$a_{43} = -\frac{1}{2} e^{\gamma_1^n L}$$

ELEMENTS OF MATRICES A AND B (Cont'd)

$$a_{44} = -\frac{1}{2} e^{\gamma_2 n L}$$

$$b_1 = 0$$

$$b_2 = p_n \frac{L}{F_n}$$

$$b_3 = 0$$

$$b_4 = \cos 30^\circ L \left[\frac{F_n}{hE} + \alpha T_n + \sum_{i=0}^{n-1} \Delta \epsilon_i^s + \frac{F_n}{h} \sum_{i=0}^{n-1} K_i - \frac{p_n L^2}{4F_n} \right]$$

APPENDIX B
LISTING OF THE DILATE PROGRAM

TABLES

<u>Table</u>	<u>Page</u>
B-1 Main Program Duct	B-3
B-2 Subroutine SOLVEQ	B-6
B-3 Subroutine CREEP	B-7
B-4 Subroutine SWELL	B-8

PROGRAM NUCT 74/74 OPT=1 — FTN 4.5+414 09/06/70 08.51.40

Neg 7911734-1

PROGRAM FLCT	76/76	CPT=1	FTN 4.5+414	09/06/79	08.51.40
--------------	-------	-------	-------------	----------	----------

9

B-4

TABLE B-1 (Cont'd)

00/06/79 08.51.40

```

140      C
      ADD=0.05*(FORCF
      DO 20 J=1,NY
      DEFL=C(1)*X(J)+C(2)+C(3)*DEXP(R1*X(J))+C(4)*EXP(P2*Y(J))-ADD*
145      1Y(J)*X(J)+0.5
      MOM=(C(1)+P1*R1*DEXP(P1*X(J))+C(4)+R2*P2*EXP(P2*Y(J))-ADD)*
      *II/CON
      SFAP=I*(C(1)+P1*3*DEXP(P1*Y(J))+C(4)+R2*3*DEXP(P2*Y(J)))/CON
150      1-FORCF*(C(1)+C(7)*R1*DEXP(R1*Y(J))+C(4)+R2*DEXP(P2*Y(J))-ADD
      1*Y(J))
      SFEND(J)=MOM*0.5*TH/II
      SIGMA(J)=SFEND(J)/STRESS
      FOR(J)=FORM*SIGMA(J)/STRESS
155      BC WRITE (6,300) X(J),STRESS,SFEND(J),SIGMA(J),FTH,ESW,FOR(J),DEFL,
      1SFAP,MOM,FORCF
      300 FORMAT (11F12.5)
      20 CONTINUE
      10 CONTINUE
      STOP
      END
160

```

CARD NR.	SEVERITY	DETAILS	DIAGNOSIS OF PROBLEM
1	1	1	1
2	2	2	2
3	3	3	3
4	4	4	4
5	5	5	5
6	6	6	6
7	7	7	7
8	8	8	8
9	9	9	9
10	10	10	10
11	11	11	11
12	12	12	12
13	13	13	13
14	14	14	14
15	15	15	15
16	16	16	16
17	17	17	17
18	18	18	18
19	19	19	19
20	20	20	20
21	21	21	21
22	22	22	22
23	23	23	23
24	24	24	24
25	25	25	25
26	26	26	26
27	27	27	27
28	28	28	28
29	29	29	29
30	30	30	30
31	31	31	31
32	32	32	32
33	33	33	33
34	34	34	34
35	35	35	35
36	36	36	36
37	37	37	37
38	38	38	38
39	39	39	39
40	40	40	40
41	41	41	41
42	42	42	42
43	43	43	43
44	44	44	44
45	45	45	45
46	46	46	46
47	47	47	47
48	48	48	48
49	49	49	49
50	50	50	50
51	51	51	51
52	52	52	52
53	53	53	53
54	54	54	54
55	55	55	55
56	56	56	56
57	57	57	57
58	58	58	58
59	59	59	59
60	60	60	60
61	61	61	61
62	62	62	62
63	63	63	63
64	64	64	64
65	65	65	65
66	66	66	66
67	67	67	67
68	68	68	68
69	69	69	69
70	70	70	70
71	71	71	71
72	72	72	72
73	73	73	73
74	74	74	74
75	75	75	75
76	76	76	76
77	77	77	77
78	78	78	78
79	79	79	79
80	80	80	80
81	81	81	81
82	82	82	82
83	83	83	83
84	84	84	84
85	85	85	85
86	86	86	86
87	87	87	87
88	88	88	88
89	89	89	89
90	90	90	90
91	91	91	91
92	92	92	92
93	93	93	93
94	94	94	94
95	95	95	95
96	96	96	96
97	97	97	97
98	98	98	98
99	99	99	99
100	100	100	100

41 I AM IF STATEMENT MAY BE MORE EFFICIENT THAN A 2 OR 3 BRANCH COMPUTED GO TO STATEMENT.
92 I AM IF STATEMENT MAY BE MORE EFFICIENT THAN A 2 OR 3 BRANCH COMPUTED GO TO STATEMENT.

TABLE B-2

SUBROUTINE SOLVEQ

SUBROUTINE SWELL 74774 OPT=1 FTN 4.5*414 09/06/79 08.51.40

```

1      SUBROUTINE SWELL (TEMPK,FLU,ESW)
      C
      C      NSMH, REV. 5 IRRADIATION SWELLING
      C      TEMPK = TEMPERATURE, K
      C      FLU = FAST NEUTRON FLUENCE, N/CM2
      C      ESW = IRRADIATION SWELLING STRAIN
      C
      ALPHA=2.
      TAUS=7.
      DEL=(TEMPK-773.)/100.
      RS=EXP(0.0419+1.498*DEL+0.122*DEL*DEL-0.332*DEL**3-.441*DEL**4)
      FLUS=FLU*1.E-22
      ESW=RS*(FLUS*ALOG((1.+EXP(ALPHA*(TAUS-FLUS)))/(1.+EXP(ALPHA*TAUS)))
      17/ALPHA)/300.
15     RETURN
      END

```

SYMBOLIC REFERENCE MAP (R=1)

ENTRY POINTS
3 SWELL

VARIABLES	SN	TYPE	RELOCATION	61	DEL	REAL	
57 ALPHA		REAL					
0 ESW		REAL	F.P.	0	FLU	REAL	F.P.
63 FLUS		REAL		62	RS	REAL	
60 TAUS		REAL		0	TEMPK	REAL	F.P.

EXTERNALS	TYPE	ARGS		FXP	REAL	1 LIBRARY
ALOG	REAL	1 LIBRARY				

STATISTICS			
PROGRAM LENGTH	648	52	

Neg 7911734-5

TABLE B-3

SUBROUTINE CREEP

SUBROUTINE CREEP

74/74 OPT=1

FTN 4,5+414

09/06/79 08.51.40

PAGE 1

```

1      SUBROUTINE CREEP (STRESS,TEMPK,FLU,FCRM)
      C
      C      NSMH, REV. 3 IRRADIATION CREEP, UNIAXIAL TENSION
      C      STRESS - STRESS,PSI
5      C      TEMPK - TEMPERATURE,K
      C      FLU - FAST NEUTRON FLUENCE,N/CM2
      C      ECRM - IRRADIATION CREEP STRAIN
      C
      C      DOUBLE PRECISION CON1,CON2,CON3,BBAR
10     A=8.4E-9
      TTR=.043E22
      RC=1.987
      TAUC=7.E22
      B0=3.E-30
15     RT=RC*TEMPK
      CON2=-16000./RT
      CON3=5.*CON2
      CON1=1.-1./EXP(FLU/TTR)
      BBAR=7.2E-25*DEXP(CON2)*(FLU-TAUC*(1.-1./EXP(FLU/TAUC)))/
20     I(1.*?0.1)*DEXP(CON3)*FLU*80
      FCRM=(A*CON1+BBAR)*STRESS
      RETURN
      END
  
```

SYMBOLIC REFERENCE MAP (P=1)

ENTRY POINTS

3 CREEP

VARIABLES	SN	TYPE	RELOCATION			
122 A	REAL			120	BBAR	DOUBLE
126 B0	REAL			112	CON1	DOUBLE
114 CON2	DOUBLE			116	CON3	DOUBLE
0 ECRM	REAL		F.P.	0	FLU	REAL
124 RC	REAL			127	RT	REAL
0 STRESS	REAL		F.P.	125	TAUC	REAL
0 TEMPK	REAL		F.P.	123	TTR	REAL

EXTERNALS

TYPE ARGS

DEXP DOUBLE 1 LIBRARY EXP REAL 1 LIBRARY

STATISTICS

PROGRAM LENGTH

1303

88

Neg 7911734-6

TABLE B-4

SUBROUTINE SWELL

SUBROUTINE SOLVER 74/74 CRT-1

FTN 4,5,414

08/04/78 08.51.40

```

1      SUBROUTINE SOLVER(A,B,NF,NRHS,X)
      DOUBLE PRECISION A(4,4),F(4,1),X(4,1),C(4,5)
      INTEGER ROW,COL
      MK = NF + NRHS
      DO 10 J = 1,NF,1
      DO 10 I = 1,NF,1
      C(I,J) = A(I,J)
12     CONTINUE
      DO 15 I = 1,NF
      DO 14 J=1,NRHS
      K=NF+J
      C(I,K) = B(I,J)
14     CONTINUE
15     CONTINUE
      ROW = 1
      HIGH = 0.00
      COL = ROW
      DO 1 I = ROW,NF
      TEST = C(I,COL)
20     IF (ABS(TEST) .LT. ASSOCIATED(0) .AND. TEST .NE. 0)
      HIGH = TEST
      IMAX = I
      1 CONTINUE
      DO 2 J = COL, MK
      C(IMAX,J) = C(IMAX,J)/HIGH
      DO 3 I = 1, NF
      IF (I .EQ. IMAX) GO TO 3
      CONST = C(I,COL)
      DO 3 J = COL, MK
      C(I,J) = C(I,J) - CONST * C(IMAX,J)
      3 CONTINUE
      DO 4 J = 1, NRHS
      SAVE = C(ROW,J)
      C(ROW,J) = C(IMAX,J)
35     C(IMAX,J) = SAVE
      ROW = ROW + 1
      IF (ROW .GT. NF) GO TO 6
      40 TO 4
      4 CONTINUE
      DO 5 I = 1,NF
      DO 7 J = 1, NRHS
      K = NF + J
      X(I,J) = C(I,K)
      7 CONTINUE
45     CONTINUE
      RETURN
      END

```

B-8

SYMBOLIC REFERENCE MAP (P=1)

ENTRY POINTS

SOLVER

Neg 7911734-3