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# ROBOT3 - A COMPUTER PROGRAM TO CALCULATE THE IN-PILE THREE-DIMENSIONAL BOWING OF CYLINDRICAL FUEL RODS

(AWBA Development Program)

S.E. KOVSCEK
S. E. MARTIN

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OCTOBER 1982

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BETTIS ATOMIC POWER LABORATORY
PITTSBURGH, PENNSYLVANIA 15122-0079
Operated for the U. S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

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# FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Atomic Energy Commission (now Department of Energy, DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and will finish routine power operation on October 1, 1982. After End-of-Life core testing, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U. S. industry in evaluating the LWBR concept for commercial-scale applications. The AWBA program, which is concluding in September, 1982, has explored some of the problems that would be faced by industry in adopting technology confirmed in the LWBR program. Information already developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been conducted under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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# ABSTRACT


ROBOT3 - A Computer Program to Calculate the In-Pile Three-Dimensional Bowing of Cylindrical Fuel Rods

ROBOT3 is a FORTRAN computer program which is used in conjunction with the CYGRO5 computer program to calculate the time-dependent inelastic bowing of a fuel rod using an incremental finite element method. The fuel rod is modeled as a viscoelastic beam whose material properties are derived as perturbations of the CYGRO5 axisymmetric model. Fuel rod supports are modeled as displacement, force, or spring-type nodal boundary conditions. The program input is described and a sample problem is given.

# ROBOT3: A Computer Program to Calculate the In-Pile Three-Dimensional Bowing of Cylindrical Fuel Rods

S. E. Kovscek

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## I. Introduction

In most nuclear reactor core designs the fuel is contained in long cylindrical tubes supported at intervals along their lengths by support grids. The tubes are called cladding and the fuel-cladding assemblage is usually referred to as a fuel rod. Within the reactor core operating environment a number of factors such as transverse temperature gradients, transverse neutron flux gradients, axial forces, cladding wall thickness variation, and support misalignment can cause a fuel rod to bow laterally between the supports. ROBOT3 is a FORTRAN computer program which is used in conjunction with the CYGRO5 computer program (Reference [1]) to calculate the time-dependent inelastic bowing of a fuel rod. The ROBOT3 computer program and its use are described in this report. The mathematical model used in ROBOT3 is developed in detail in Reference [2] and is described only briefly here.

A variational method for calculating the two-dimensional (i.e., single plane) bowing of fuel rods was originally developed by Newman in Reference [3] and later formed the basis for the ROBOT computer program (Reference [4]). The ROBOT3 program is derived from the ROBOT program; however, the mathematical model has been reformulated and extended, and the program has been extensively re-written. In ROBOT3 the fuel rod is modeled as a three-dimensional space curve with each material point along the curve having two components of lateral displacement and one component of axial displacement. These displacement components are calculated simultaneously using a new finite element formulation developed in Reference [2]. ROBOT3 also has the capability for modeling the bowing behavior of fuel rods containing either single-zone or duplex fuel pellets.

With duplex fuel, the fuel consists of two zones — a central cylindrical zone of one material surrounded by an annular zone of a different material. In some cases the central region may also be annular and contain a central void. ROBOT3 contains a model for predicting the effect of fuel-fuel and fuel-cladding contact interaction on the rod bowing. This model is an extension of the one currently used in the ROBOT program.

In Section II of this report the ROBOT3 mathematical model and numerical solution procedure are briefly described. The reader is referred to Reference [2] for a more complete description. In Section III the card input format for the ROBOT3 program is described in detail. Where appropriate, additional description of the mathematical model is given. In Section IV a sample problem is set up and solved using ROBOT3 and examples of the program input and output are given.

## II. The ROBOT3 Mathematical Model

In ROBOT3 the fuel rod is modeled as a three-dimensional space curve representing the centroidal axis of the cladding. In a rectangular cartesian coordinate system the rod is assumed to lie principally along the z-axis. Denoting the x-, y-, and z-displacements of the rod by u, v, and w, respectively, it is assumed that these displacements and the quantities $\frac{du}{dz}$, $\frac{dv}{dz}$, and $\frac{dw}{dz}$ are small. The rod is supported at intervals along its length by support grids. Each of the rod spans between the supports is divided into a user-specified number of equal length finite elements. Within each finite element the lateral displacements are approximated by third degree polynomials (Hermite interpolation functions) and the axial displacements are adjusted to make the axial strain uniform within the element. Each element has two nodes (one at each end) with five degrees-of-freedom at each node. The five degrees of freedom are u, v, w, $\frac{du}{dz}$, $\frac{dv}{dz}$ evaluated at the node. These quantities are the primitive variables which the program calculates as functions of time. Displacements at points other than the nodes are calculated using the finite element interpolation functions.

The rod supports are modeled by imposing boundary conditions at nodes corresponding to the support positions. The boundary conditions can be either force-type, displacement-type, or spring-type. Since there are three translational and two rotational degrees of freedom at each support, the terms force-type and displacement-type are used here in the generalized sense. For the rotational degrees-of-freedom, a force-type boundary condition corresponds to an imposed moment and a displacement-type boundary condition corresponds to an imposed slope. Similarly, spring-type boundary conditions are either torsional or translational. To better model flexible supports and spring liftoff behavior a provision has been made for modeling a support with positive-side and negative-side contact springs. This model is discussed more fully in Section III.

ROBOT3 calculates the rod deflection as a function of time by taking small time steps and summing the displacement increments. The time steps which ROBOT3 takes are specified on a data file written by the CYGRO5 program (Reference [1]). For each time step this file also contains information which ROBOT3 uses to construct the incremental moment-curvature relation (i.e. constitutive equation) for the rod. Like CYGRO5, ROBOT3 approximates the axial-direction material property variation as piecewise constant. Each axial location in the ROBOT3 model derives its material properties from the corresponding axial location in the CYGRO5 model. Although it is recommended that the ROBOT3 finite element distribution be such that material property changes occur at element boundaries, this is not a requirement.

Transverse gradients of the temperature and fast-neutron flux induce moment-free curvatures in the rod which affect the fuel rod bowing. The x- and y-components of the fast-neutron flux gradient are specified by the user in the ROBOT3 input. The user must also specify the x- and y-components of the volumetric heat generation gradient in the fuel, the coolant temperature gradient, and the clad-to-coolant film coefficient gradient. ROBOT3 uses these three gradients to internally calculate the transverse temperature distribution within the fuel rod.

Fuel rod bowing is also strongly influenced by the initial free shape of the centroidal axis. To specify the initial free shape of the centroidal axis, the user inputs data for the centerline deflection and the cladding wall-thickness eccentricity at various axial locations. The x- and y-components of the cladding wall-thickness eccentricity are defined to be the distances $e_x$ and $e_y$ shown in Figure 1. ROBOT3 uses the finite element shape functions to determine a modified least-squares fit to the free shape and eccentricity data. The details of this method are contained in Reference [2].

The bowing behavior of the fuel rod is also affected by contact interaction between the fuel and the cladding and, with duplex fuel, by contact interaction between the fuel zones. Such contact may be established and broken several times during the operational history of the fuel rod. Information on when such interaction occurs is calculated by CYGRO5 and communicated to ROBOT3 in the CYGRO5 bowing data file. When, for example, fuel-clad contact is established, there will in general be a sudden jump in the cladding curvature and there will be a change in the moment-curvature relation for the rod. Experiments have shown, however, that these changes are not generally as large as would be calculated using the assumption that the cladding and fuel have equal curvatures after contact is established. The interaction model in ROBOT3 is based upon the assumption that an elastic-viscous interaction element couples the curvatures of the cladding and the outer fuel zone. It is assumed that another such element couples the curvatures of the two fuel zones. Because this flexural coupling can be difficult to visualize (and to illustrate), Figure 2 shows an analogous system of coupled linear spring elements. In this diagram, force is analogous to moment and displacement is analogous to curvature.

To specify the nature of the contact interaction between the fuel zones and between the fuel and the cladding, three parameters are specified for each of the interaction elements. These parameters are

(1) the contact efficiency $\gamma$,

(2) the elastic bending efficiency $\eta$, and

(3) the bending viscosity ratio $\beta$.

When contact is established between the fuel and cladding or between the fuel zones, there will be jumps in their curvatures. The contact efficiency $\gamma$ is the ratio of the observed changes to the changes which would occur if there were perfect interaction (i.e. equal curvatures after contact). The elastic bending efficiency $\eta$ is used to define the elastic flexural stiffness of the interaction elements using the formula

$$G = \left(\frac{\eta}{1 - \eta}\right) G_{inner}$$

where G is the flexural stiffness of the interaction element and $G_{inner}$ is the flexural stiffness of the inner of the two elements which are in contact. In other words, for fuel-cladding contact $G_{inner}$ refers to the outer fuel zone; for fuel-fuel contact $G_{inner}$ refers to the inner fuel zone. Note that when $\eta = 0$, then $G = 0$ and there is no interaction. As $\eta$ approaches 1, G approaches infinity and the interaction element becomes rigid. The bending viscosity ratio $\beta$ is used to define the flexural viscosity of the interaction elements using the formula

$$W = \beta\, W_{inner}$$

where W is the bending viscosity of the interaction element and $W_{inner}$ is the bending viscosity of the inner of the two elements which are in contact. Note that setting $\beta$ to a very large number makes the interaction element behave elastically.

In summary, there are several basic steps to performing a rod bowing analysis using CYGRO5 and ROBOT3. The first step is to run CYGRO5 and create a bowing analysis file as described in Reference [1]. Once this file is created it can be used for a number of ROBOT3 analyses. The basic steps for setting up the ROBOT3 input are

(1) specify the support positions and the number of finite elements in each span,

(2) input initial centerline deflection and cladding eccentricity data,

(3) specify the time-dependent boundary conditions at the supports,

(4) specify the transverse neutron flux and thermal gradients,

(5) specify the fuel-fuel and fuel-clad interaction constants, and

(6) specify the output edits desired.

The details of setting up the ROBOT3 input are given in the next section.

## III. Input Description

ROBOT3 input is in Bettis Input Package form as given in Reference [5]. In particular, input cards need not be sorted; data is converted according to the format of the card ("free field"); and redundant cards are removed automatically using the last occurrence of a card as the valid entry. This accommodates easy input deck modification.

All input cards are listed in the printed output. Comment information may follow the data on any card if a dollar sign is punched between the last data item and the comment. An asterisk or a dollar sign in the first non-blank column denotes a card containing only comments. One of the cards in an input deck should be a title card, denoted by an equal sign in the first non-blank column. The information on this card is used to title each page of printer output. If more than one title card is present, the last such card is used. Blank cards in the input deck are ignored.

The first field on a data card is an integer which represents the CARD NUMBER and is followed by a comma. Data cards are divided into fields of arbitrary length, with the fields separated by commas and the comma following the last field optional. Each field contains an integer number, a floating point number, or an alphanumeric identifier. Leading and trailing blanks are ignored in all fields, and embedded blanks are ignored in numeric fields.

The integer format is:

Sxx...xx

and the floating point format is:

Sxx...xxSyy,

where the S stands for either a plus (+) sign or a minus (-) sign and where the leading sign may be dropped if it is plus and where each x and y is a decimal digit or a blank. In the floating point format the decimal point is assumed to precede the fractional part and the signed one or two digit exponent must be present. The presence of any other character, such as a letter, causes the rejection of the data as invalid. The floating point format may optionally be signified by using a decimal point in the fractional part, and in this form, the signed one or two digit exponent is optional.

An alphanumeric field must contain at least one non-numeric character or must be enclosed in parentheses. A non-numeric character is any character other than +, -, ., 0 through 9, or the blank character. All cards may be continued indefinitely by designating a continuation card as one which has a plus sign as the first non-blank character.

The input is divided into cases. There are two ways to designate the end of input for a case. One way is a card whose first non-blank character is a period (.) which means an end of input for the job. The second way is a card whose first non-blank character is a slash (/) which means an end of input for the case with subsequent input cases. In multiple case problems, the program starts each case at time zero and the input from the previous case is carried over so that only cards which change need to be input.

The majority of variables are entered in "floating point" format. Thus, the type of variable will be indicated in the card write-up only when it is "integer" or "alphanumeric" rather than "floating point". An "alphanumeric" input variable must be given exactly as indicated here. Floating point zeros must include a decimal point.

If any card is not used by the program, its number is printed in the problem output. This serves as a useful check in input preparation, for errors in card numbering often lead to a card number that will not be used.

1. <u>CYGRO5 Input File</u>

   100, synonym, version, prefix, file id $(Required)

   The program allows a complete description of the CYGRO5 file to be input except for the datatype where a value of 345 is used. However, only the synonym is required. The file must be FETCHed by the job.

   Synonym - (Alphanumeric) A 1 to 7 character id assigned to the file (Required).

   Version - (Integer) The version number of the file (Optional).

   Prefix - (Alphanumeric) The four character prefix (P = ) of the file (Optional).

   File id - (Alphanumeric) The file identification (I = ) of the input file (Optional).

2. Integration Accuracy

111, NPASS $ (Optional)

NPASS - (Integer) The number of passes within a timestep for time integration accuracy. A "1" indicates one pass will be made for computing the nodal incremental displacements within a timestep. A "2" indicates two passes are made within a timestep. It is recommended that a value of "2" be used and this is the default value.

In a one pass problem, the beginning of timestep values of nodal displacements are used for evaluating the strain rate and element stiffness matrix for determining the nodal displacement increments. In a two pass problem, the first pass is taken as before. The averaged nodal displacements during the time step are then used in evaluating the strain rate and element stiffness matrices used in a second pass.

3. Initial Boundary Conditions

121, NTIMBC $ (Optional)

NTIMBC - (Integer) The number of timesteps to take for applying initial boundary conditions. The program takes NTIMBC timesteps whose time increments are $10^{-6}$/NTIMBC hours to apply initial boundary conditions. The default value is 4 because this is adequate for most problems.

4. Number of Finite Elements in the Rod

1000, NELEM1, NELEM2, ... NELEMN $ (Required)

All entries are integers.
The number of finite elements in each span. There must be an entry corresponding to each span. The minimum number of elements in a span is one while there is no limit (except for core storage) on a maximum value.
The number of entries must be one less than the number of supports. (See cards 1001-1009).

5. Support Locations (1001-1009)

1001, $Z_1$, $Z_2$, ..., $Z_n$ \$ (Required)

All entries are floating point.
The list of axial coordinates of the supports. $Z_1$ is the first support location and $Z_n$ is the last support location. The list of axial coordinates must be in ascending order. A maximum of 99 support locations are permitted. Units are inches.

6. Clad Free Shape (Optional)

In many cases the free shape of the beam is not straight. The card series 1010-1110 describes the free shape coordinates in x and y as a function of axial position.

1010, $Z_1$, $X_1$, $Y_1$, $Z_2$, $X_2$, $Y_2$, ... $Z_n$, $X_n$, $Y_n$

$Z_1$ - The axial coordinate for free shape data. Units are inches.
$X_1$ - The X-direction free shape coordinate at axial location $Z_1$. Units are inches.
$Y_1$ - The Y-direction free shape coordinate at axial location $Z_1$. Units are inches.

The axial coordinates must be in ascending order. One hundred axial coordinates are permitted. If this card series is omitted then the clad free shape is assumed to be straight. The program does a least squares fit of the data as described in Section V of Reference [2].

7. Eccentricity (Optional)

The eccentricity is input on card series 3010-3100.

3010-3100, $Z_1$, $e_{x,1}$, $e_{y,1}$, ..., $Z_n$, $e_{x,n}$, $e_{y,n}$

$Z_1$ - The axial coordinate for eccentricity data. Units are inches.
$e_{x,1}$ - The X-component of the eccentricity at axial location $Z_1$. Units are inches.
$e_{y,1}$ - The Y-component of the eccentricity at axial location $Z_1$. Units are inches.

7. Eccentricity (Optional) (Cont'd)

The restrictions are the same as for the clad free shape input card series 1010-1100. The program does a least squares fit of the data as described in Section V of Reference [2].

8. Boundary Conditions

There are three types of boundary condition input which may be specified at a support. The boundary conditions types are force, displacement and flexible (springs) and are input on cards 10000, 11000, and 12000 respectively. Figure 3 shows a representation of various types of boundary conditions which can be used to model rod supports. For simplicity only the X-Z plane is shown. At support 1, force boundary conditions are assumed for all degrees of freedom while at support 2 displacement boundary conditions are applied. At support number 3, flexible boundary conditions are applied to all degrees of freedom and a support axial displacement is also assumed. At support 4 a displacement boundary condition is applied in the X-direction, and a rotational force (i.e. a moment) boundary condition is applied in the X-Z plane.

At each support there are five degrees of freedom which are translational in X, Y, and Z and rotational in X-Z and Y-Z. The input card has the form BBNSS where BB is 10, 11, and 12 for boundary condition types of force, displacement and flexible respectively, N is the degree of freedom, and SS is the support number. See Table 1 for the relationship among card numbers, type of boundary condition and degree of freedom.

Only the supports that have anything other than a zero force or zero moment boundary condition need to be input. If no boundary condition is input then the support is assumed to be free. Conflicting boundary conditions may not be input. Specifically, a displacement boundary condition may not be input with any other type for the same support and degree of freedom.

TABLE 1

Forces

| | |
|---|---|
| 101SS | lateral force in X-direction |
| 102SS | rotational force (moment) in X-Z plane |
| 103SS | lateral force in Y-direction |
| 104SS | rotational force in Y-Z plane |
| 105SS | lateral force in Z-direction |

Displacements

| | |
|---|---|
| 111SS | lateral displacement in X-direction |
| 112SS | slope in X-Z plane |
| 113SS | lateral displacement in Y-direction |
| 114SS | slope in Y-Z plane |
| 115SS | lateral displacement in Z-direction |

Flexible (Spring Constants)

| | |
|---|---|
| 121SS | lateral spring in X-direction |
| 122SS | torsional spring in X-Z plane |
| 123SS | lateral spring in Y-direction |
| 124SS | torsional spring in Y-Z plane |
| 125SS | lateral spring in Z-direction |

8. Boundary Condition Input Discussion (Cont'd)

There is a minimum set of boundary conditions which must be specified in order to have a well-defined problem. The minimum boundary condition set for the X and Y directions can be specified in two ways. One way is for a lateral displacement or lateral spring to be input at any two distinct supports. The other is for a lateral displacement or lateral spring to be input at any support and a rotational displacement or torsional spring to be input at any support. The Z-direction must have a lateral displacement or spring boundary condition applied to at least one support.

The force and displacement boundary condition input cards have the same format. Constant and time varying data are input as follows:

BBNSS, X

or

BBNSS, $t_1$, $X_1$, $t_2$, $X_2$, ... $t_k$, $X_k$.

If one value is supplied then that value X is held constant throughout time. If a table of values is given, the value of X is determined by piecewise linear interpolation. If time is greater than $t_k$ then $X_k$ will be held for the rest of the problem. The assumed positive directions for forces and moments are shown in Figure 4. A maximum of 30 times are permitted. The input on the following cards are floating point unless stated otherwise.

8.1.1. X-Direction Lateral Force

101SS, F

or

101SS, $t_1$, $F_1$, ... $t_k$, $F_k$

$t_i$ - time in hours

$F_i$ - X-direction transverse force on support SS at time $t_i$. Units are pounds

8.1.2. X-Direction Rotational Force

102SS, M

or

102SS, $t_1$, $M_1$, ... $t_k$, $M_k$

$t_i$ - time in hours

$M_i$ - the moment in the X-Z plane for support SS at time $t_i$. Units are inch-pounds.

8.1.3. Y-Direction Lateral Force

103SS, F

or

103SS, $t_1$, $F_1$, ... $t_k$, $F_k$

$t_i$ - time in hours

$F_i$ - Y-direction transverse force on support SS at time $t_i$. Units are pounds.

8.1.4. Y-Direction Rotational Force

104SS, M

or

104SS, t, $M_1$, ... $t_k$, $M_k$

$t_i$ - time in hours

$M_i$ - moment in Y-Z plane for support SS at time $t_i$. Units are inch-pounds.

8.1.5. Z-Direction Force

105SS, F

or

105SS, $t_1$, $F_1$, ... $t_k$, $F_k$

$t_i$ - time in hours

$F_i$ - the axial force for support SS at time $t_i$. Units are pounds.

8.2.1. X-Direction Translational Displacement

111SS, a

or

111SS, $t_1$, $a_1$, ... $t_k$, $a_k$

$t_i$ - time in hours

$a_i$ - the X-direction coordinate of rod at support SS at $t_i$. Units are inches

8.2.2. X-Direction Rotational Displacement

112SS, b

or

112SS, $t_1$, $b_1$, ... $t_k$, $b_k$

$t_i$ - time in hours

$b_i$ - the rod slope in the X-Z plane at support SS at time $t_1$. Units are inch/inch.

8.2.3. Y-Direction Translational Displacement

113SS, a

or

113SS, $t_1$ $a_1$, ... $t_k$, $a_k$

$t_i$ - time in hours

$a_i$ - the rod Y-coordinate at support SS at time $t_i$. Units are inches.

8.2.4. Y-Direction Rotational Displacement

114SS, b

or

114SS, $t_1$ $b_1$, ..., $t_k$, $b_k$

$t_i$ - time in hours

$b_i$ - the rod Y-Z slope at support SS at time $t_i$. Units are inch/inch.

8.2.5. Z-Direction Translational Displacement

115SS, a

or

115SS, $t_1$, $a_1$ ..., $t_k$, $a_k$

$t_i$ - time in hours

$a_i$ - the rod Z-coordinate at support SS at time $t_i$. Units are inches.

8.3. Flexible Boundary Condition Discussion

Flexible, or spring-type, boundary conditions can be applied to each of the nodal degrees-of-freedom. All of the springs are connected to a support whose position and orientation can vary with time. The force- or moment-free position of the spring is defined to be constant relative to the support position. To more accurately model the actual rod support mechanism and to model the spring liftoff behavior, it is assumed that both positive-side and negative-side springs can act on the lateral displacement and rotational degrees-of-freedom. A negative-side spring is defined as one which can only exert a positive direction force or moment on the rod. For lateral displacements, this corresponds to the physical notion of a spring located on the negative side of the rod which can push against the rod if in contact, but can never pull on the rod. Similarly, a positive-side spring is one which can only push the rod in the negative direction. This concept is illustrated in Figure 5 for the case of a lateral displacement degree-of-freedom. For torsional springs, the concept is more difficult to visualize but is mathematically and conceptually the same. For the axial direction, a single spring is used and this spring, if present, is assumed to be attached to the rod throughout the problem.

8.3.1. X-Direction Lateral Spring

There are three card formats for flexible boundary condition input depending upon the displacement of the support. The support displacement may be constant or time varying. The support is held at 0.0 displacement if no displacement data is input.

121SS, K1, FRESP1, K2, FRESP2

or

121SS, K1, FRESP1, K2, FRESP2, d

or

121SS, K1, FRESP1, K2, FRESP2, $t_1$, $d_1$, ... $t_k$, $d_k$

K1 - The lateral spring constant in X-direction for a spring on the positive side of the rod. Units are lbs/in.

FRESP1 - The free position X-coordinate relative to the support for a positive side spring (i.e. the X-coordinate of the spring where no force is exerted on the rod). The spring breaks contact with the rod when the calculated displacement is less than the free position coordinate plus the support displacement.

K2 - The lateral spring constant in X-direction for a spring on the negative side of the rod.

FRESP2 - The free position X-coordinate relative to the support for a negative side spring. The spring breaks contact with the rod when the calculated displacement is greater than the free position coordinate plus support displacement.

d - The support displacement which is held constant throughout time. Units are inches. Default value is 0.0.

$t_1$ - time in hours.

$d_1$ - The displacement of the support at time $t_1$. Units are inches.

8.3.1. X-Direction Lateral Spring (Cont'd)

Four entries are required on the card. If there is a spring on only one side of the rod, input zeros for the spring input for the side with no spring. The support is assumed to be at zero if support displacements are not input. A maximum of 30 pairs of time-displacements are permitted.

8.3.2. X-Z Plane Torsional Spring

122SS, K1, FRESP1, K2, FRESP2

or

122SS, K1, FRESP1, K2, FRESP2, d

or

122SS, K1, FRESP1, K2, FRESP2, $t_1$, $d_1$, ... $t_k$, $d_k$

K1 - The torsional spring constant in the X-Z plane for a positive-side spring. Units for K1 and K2 are inch-lbs/inch/inch.

FRESP1 - The free position X-Z slope relative to the support for a positive side spring (i.e. the X-Z slope of the spring where no moment is exerted on the rod). The spring breaks contact with the rod when the calculated slope is less than the free position slope plus the support slope.

K2 - The torsional spring constant in the X-Z plane for a negative-side spring.

FRESP2 - The free position X-Z slope relative to the support for a negative side spring. The spring breaks contact with the rod when the calculated slope is greater than the free position slope plus the support slope.

d - The support slope which is held constant throughout time. Units are inch/inch. Default value is 0.0.

or for time varying slopes.

$t_1$ - time in hours.

$d_1$ - The slope of the support at time $t_1$. Units are inch/inch.

8.3.3. Y-Direction Lateral Springs

123SS, K1, FRESP1, K2, FRESP2

or

123SS, K1, FRESP1, K2, FRESP2, d

or

123SS, K1, FRESP1, K2, FRESP2, $t_1$, $d_1$, ... $t_k$, $d_k$

The Y-direction lateral spring input. See card 121SS for description of input variables.

8.3.4. Y-Z Plane Torsional Springs

124SS, K1, FRESP1, K2, FRESP2

or

124SS, K1, FRESP1, K2, FRESP2, d

or

124SS, K1, FRESP1, K2, FRESP2, $t_1$, $d_1$, ... $t_k$, $d_k$

The Y-direction torsional spring input. See card 122SS for description of input variables.

8.3.5. Axial Spring Input

125SS, K1, FRESP1, K2, FRESP2

or

125SS, K1, FRESP1, K2, FRESP2, d

or

125SS, K1, FRESP1, K2, FRESP2, $t_1$, $d_1$, ..., $t_k$, $d_k$

See card 121SS for a description of the input variables. The variables on this card refer to axial direction displacements and spring constants. The axial springs are assumed to be attached to the rod at all times.

9. Output Times

31000, WRITE/PLOT, $t_1$, $t_2$, ... $t_N$ $ (Optional)

WRITE/PLØT - (Alphanumeric) The character string DONT PLOT for no plots or the character string PLEASE PLOT to obtain plots of the rod at the times listed on the card. Two plots of the rod are given, one in the X-Z plane and the other in the Y-Z plane.

$t_1$ - time in hours for plotting rod shape. A maximum of 50 times are allowed.

10. Plot Options

34000, USRMAX, NGRID, NSTRIP $ (Optional)

USRMAX - (Floating) The vertical limit for plotting the rod shape and history shape. The vertical axis corresponds to the X and Y deflections. The default is to let the program decide vertical axis.

NGRID - (Integer) Option to place a grid on the plots. A 0 for no grid and a 1 for a grid. Default is 0 for no grid.

NSTRIP - (Integer) The number of strips to place on one frame. The minimum is one strip per frame to a maximum of 5 strips per frame. A negative value will join the strips vertically on a frame while a positive value has separate strips. The default is four separate strips on a frame.

11. Axial Edit Locations

33000 -33009, $Z_1$, $Z_2$, $Z_3$, ... $Z_n$ (Required)

A list of axial coordinates for which an edit is given at times listed on card series 31000 and an edit/plot is performed for the entire history at problem termination. The deflections are centerline reference for the X and Y direction. A maximum of 50 coordinates are permitted. When plotting, the vertical axis, grid, and number of strips from card 34000 are applicable.

12. Environmental Data

33010, NSEGMENT $ (Optional)

NSEGMENT - (Integer) The CYGRO5 segment for which the environmental data of pressure, temperature, and power are included in the history deflection data at problem end time. The default value is the first segment.

13. Interaction Parameters

13.1 Fuel-Clad Efficiency Parameters

70050, ETA, GAMMA, BETA $ (Optional)

ETA - The fuel-clad bending stiffness efficiency. ETA is used when fuel and clad are in contact. The value must be $0 \leq \text{ETA} < 1.0$. The default value is .999.

GAMMA - The fuel-clad contact efficiency. This parameter represents the ratio of observed curvature jumps to the curvature jumps that would be obtained if there were perfect interaction. GAMMA is used whenever fuel-clad contact occurs and is used to compute jump curvature terms. The value must be $0 \leq \text{GAMMA} < 1.0$. The default value is .999.

BETA - The bending viscosity ratio for fuel-clad interaction. A large value makes the fuel-clad interaction region elastic. Defaults to 1.0 E+6.

13.2. Fuel-Fuel Efficiency Parameters

70051, ETA, GAMMA, BETA $ (Optional)

The variables have the same meaning as those on card 70050 except that they refer to fuel-fuel interaction.

14. Gradients

70061, $A_x$, $Z_x$, $\phi_x$, $A_y$, $Z_y$, $\phi_y$ \$ (Optional)

The coefficients in computing the x and y direction gradients for the heat generation in the fuel. The subscripts indicate the x or y direction. The gradient at an axial location $z_i$ is given by

$$\text{gradient} = A \cos\left[2\pi(z_i + \phi)/Z\right]$$

where A, $\phi$ and Z are parameters used to define the shape of the function. If Z is input as 0.0, then it is set to a large number which gives a constant gradient. Similarly gradients can be input on cards 70062, 70063 and 70064 for fast flux, coolant temperature, and film coefficient on rod surface, respectively. If a gradient card is omitted, it is assumed that the gradient is zero.

15. Special Options

70070, ECCENCON, ECCENCOL, CRACK \$ (Optional)

ECCENCON - (Integer) Input a 0 or 1. A value of one sets the eccentricity contribution of induced curvature to 0.0 when fuel-clad interaction occurs. A value of zero causes the eccentricity contribution to the induced curvature to be included at all times. Defaults to 0.

ECCENCOL - (Integer) Input a 0 or 1. A value of one sets the eccentricity contribution of the induced curvature to 0.0 if there is clad collapses onto the fuel, fuel hourglassing interaction, or fuel excess temperature interaction. A value of zero causes the eccentricity contribution to the induced curvature to be included at all times. Defaults to 0.

15. Special Options (Cont'd)

CRACK - (Integer) Input a 0 or 1. A value of one causes the creep viscosity of fuel rings which are cracked to be set to a very small number. A value of zero causes cracked rings to be treated as if they were not cracked; that is, the effects of cracking are ignored.

70071, ATTACHMENT $ (Optional)

ATTACHMENT - (Integer) Input a 0 or 1. A value of 1 causes all flexible boundary condition springs to be attached at all times at all supports (i.e. lift-off is not allowed). A value of 0 allows lift-off. Defaults to 0.

16. Input Check

99999, INPUT CHECK (Optional)

The character string INPUT CHECK causes the program to check the input, then terminate.

17. Debug Output Controls

10, TIME1, TIME2, PRINT1, PRINT2, ..., PRINT9 (Optional)

TIME1 - (Floating) History time to start the edits.

TIME2 - (Floating) History time to terminate the problem. If this card is omitted the program goes through the entire history in the CYGRO5 file. For the print variables, an entry of zero will suppress the edits while an entry of one turns the edits on.

PRINT1 - (Integer) The global stiffness matrix for the free shape fit and the free shape nodal displacements.

PRINT2 - (Integer) The global stiffness matrix before boundary conditions are applied.

17. Debug Output Controls (Cont'd)

PRINT3 - (Integer) The global stiffness matrix after boundary conditions are applied.

PRINT4 - (Integer) The nodal forces, correction forces, right-hand side, and displacement increments.

PRINT5 - (Integer) The D-matrix, E-vector, strain increments, and stresses in the X, Y, and Z directions at the gauss points for all elements. See Reference [2], Section III for definitions of these quantities.

PRINT6 - (Integer) Prints the variables that are used to construct the constitutive equation. For the CYGRO5 rings, these variables are the radii, moments, axial forces, elastic moduli, creep compliances, induced curvatures, and the a's and b's. For the fuel 1, fuel 2, and cladding regions the variables are curvatures, curvature increments, axial strains, strain increments, curvature jumps, and the A's and B's. These quantities are defined in Section III of Reference [2]. The edits are done for every gauss point in all elements.

PRINT7 - (Integer) Data from the CYGRO5 file and variables used in the induced curvature calculation. This edit produces a lot of output. The edit is done for every gauss point in all elements.

PRINT8 - (Integer) The nodal centroidal and centerline deflections along with the lateral deflections at the axial locations listed on card 33000. If this entry is a one, these edits are printed regardless of the values for TIME1 and TIME2.

## IV. Sample Problem

This section gives an example of the card series input and program output edits for a typical bowing problem. The sample problem has four spans with supports located at axial coordinates 0.0, 20.0, 50.0, 80.0, and 100.0 inches. There are 3 elements in span 1, 2 elements in span 2, 2 elements in span 3, and 3 elements in span 4 for a total of 10 elements. The boundary conditions applied to the rod are indicated in Figure 6. The displacements and slopes at support 1 are all specified. Support 2 has fixed lateral displacements in X and Y, specified moments in the X-Z and Y-Z planes, torsional springs resisting the applied moments, and a specified axial force. Support 3 has specified forces in the X and Y directions. Support 4 has specified slopes in the X-Z and Y-Z planes and springs in the X and Y directions. At support 5, torsional springs act in the X-Z and Y-Z planes and an axial spring with axial support displacements is attached to the rod.

The fuel rod has an initial sinusoidal free shape in both the X and Y directions. The free shape data is input on card series 1010-1018. The CYGRO5 data file was generated using the CYGRO5 sample problem given in Reference [1]. This problem has two segments with dimensions 0.0 to 45.0 inches for segment 1 and 45.0 to 100.0 inches for segment 2. ROBOT3 computes the lateral deflections occuring in the fuel rod and reports them at the axial locations specified on card 33000. Figure 7 shows a sample of deflection plots which can be generated by ROBOT3.

```
INPUT FOR FIRST CASE.  THIS PROBLEM RAN ON  CSTR1 VERSION  2.810415            IEBK008  82/06/28   ROBOT3   KOVSC   PG    1

             = SAMPLE TEST PROBLEM
0001          100, CYGROB, 1 $ FILE FROM CYGRO5
0002          1000, 3,2,2,3 $ ELEMENTS PER SPAN
0003          1001, 0.0, 20.0, 50 0, 80.0, 100.0 $ SUPPORT POSITIONS
             **** CLAD FREE SHAPE
0004          1010, 0.0,0.0,0.0, 5.0, .0011, .0011, 10.0, .00195, .00195
0005          1011, 15.0,.0026,.0026, 20.0,.003,.003, 25.0,.0029,.0029
0006          1012, 30.0,.0026,.0026, 35.0,.00213,.00213, 40.0,.00155,.00155
0007          1013, 45.0,.0008, .0008, 50.0,0.0,0.0, 55.0,-.00065,-.00065
0008          1014, 60.0,-.00121,-.00121, 65.0,-.00165,-.00165
0009          1015, 70.0,-.0019,-.0019, 75.0,-.002,-.002,
0010          1016, 80.0, -.002,-.002, 85.0,-.00175,-.00175,
0011          1017, 90.0,-.00135,-.00135, 95.0,-.0008,-.0008
0012          1018, 100.0,0.0,0.0
             *** BOUNDARY CONDITIONS - FIXED DISPLACEMENTS
0013          11101, 0.0, $ FIX X AT SUPPORT 1
0014          11201, 0.01 $ FIX SLOPE IN X-Z PLANE AT SUPPORT 1
0015          11301, 0.0  $ FIX Y AT SUPPORT 1
0016          11401, 0.01 $ FIX SLOPE IN Y-Z PLANE AT SUPPORT 1
0017          11501, 0.0  $ FIX Z AT SUPPORT 1
             *
0018          11102, 0.0 $  FIX X AT SUPPORT 2
0019          11302, 0.0 $  FIX Y AT SUPPORT 2
             *
0020          11204,0.0,0.0,500.0,0.05 $ FIX SLOPE USING TIME DEPENDENT TABLE SUPPORT 4
0021          11404,0.0,0.0,500 0,0.05 $ FIX SLOPE USING TIME DEPENDENT TABLE SUPPORT 4
             *
             * FORCE BOUNDARY CONDITION
0022          10103, 25.0 $ X-FORCE AT SUPPORT 3
0023          10303, 25.0 $ Y-FORCE AT SUPPORT 3
0024          10202, 0.0,10.0,50.0,20.0 $ X-MOMENT AT SUPPORT 2
                  +,100.0,30.0,500.0,35.0 $ CARD 10202 CONTINUED
0025          10402, 0.0,10.0,50.0,20.0 $ Y-MOMENT AT SUPPORT 2
                  +, 100.0,30.0,500.0,35.0 $ CARD 10402 CONTINUED
0026          10502,0.0,30.0,50.0,20.0,100.0,10.0,500.0,0.0 $ Z-FORCE AT SUPPORT 2
             * FLEXIBLE BOUNDARY CONDITIONS
0027          12505,1.5,0.0,0.0,0.0, 1.0-4 $ AXIAL SPRING AT SUPPORT 5 WITH DISPLACEMENTS
0028          12104,2.5,0.0,2.5,0.0 $ X-LATERAL SPRING AT SUPPORT 4
0029          12304,2.5,0.0,2.5,0.0 $ Y-LATERAL SPRING AT SUPPORT 4
0030          12202, 1.7,0.0,1.7,0.0 $ X-TORSIONAL SPRING AT SUPPORT 2
0031          12402, 1.7,0.0,1.7,0.0 $ Y-TORSIONAL SPRING AT SUPPORT 2
0032          12205, 2.3,0.0,2.3,0.0 $ X-TORSIONAL SPRING AT SUPPORT 5
0033          12405, 2.3,0.0,2.3,0.0 $ Y-TORSIONAL SPRING AT SUPPORT 5
0034          10, 100.0, 100.7,/8/0
0035          33000, 0.0, 25.0, 50.0, 75.0, 100.0
0036          33010,1
0037         31000, PLEASEPLOT, .02, 50.0, 100.0, 1000.0
             .........
```

| | | BOUNDARY CONDITIONS | | | | |
|---|---|---|---|---|---|---|
| SUPPORT | Z-CORR | X | X-Z | Y | Y-Z | Z |
| 1 | 0.000 | DISPLACE | DISPLACE | DISPLACE | DISPLACE | DISPLACE |
| 2 | 20.000 | DISPLACE | FOR-FLEX | DISPLACE | FOR-FLEX | FORCE |
| 3 | 50.000 | FORCE | FREE | FORCE | FREE | FREE |
| 4 | 80.000 | FLEXIBLE | DISPLACE | FLEXIBLE | DISPLACE | FREE |
| 5 | 100.000 | FREE | FLEXIBLE | FREE | FLEXIBLE | FLEXIBLE |

FOR THIS PROBLEM THE FUEL-CLAD BENDING INTERACTION IS GOVERNED BY THE FOLLOWING COEFFICIENTS
FUEL-CLAD DIAMETRAL INTERFERENCE. ETA-CON = 1.0000
EFFICIENCY AT BEGINNING OF INTERACTION. GAMMA = 1.0000
FUEL-CLAD BENDING VISCOSITY EFFICIENCY. BETA =1000000+07

FOR THIS PROBLEM THE FUEL-FUEL BENDING INTERACTION IS GOVERNED BY THE FOLLOWING COEFFICIENTS
FUEL-FUEL DIAMETRAL INTERFERENCE. ETA-CON = 1.0000
EFFICIENCY AT BEGINNING OF INTERACTION. GAMMA = 1.0000
FUEL-FUEL BENDING VISCOSITY EFFICIENCY. BETA =1000000+07

////////////////////////////////////////////////////////////////////////////////////////////////////

MODELING OPTIONS USED

THE EFFECT OF CLADDING CIRCUMFERENTIAL WALL THICKNESS VARIATION (ECCENTRICITY) ON BENDING CREEP RATES WILL BE INCLUDED AT ALL TIMES.

FUEL RINGS WITH TRANSVERSE CRACKS WILL BE DISREGARDED IN ALL STIFFNESS CALCULATIONS. THE FREE CURVATURE WILL BE UNCHANGE BY CRACKING.

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THE ROD HISTORY FOR THIS JOB IS FROM AN A.F.M. FILE WITH PREFIX *IEBK*, IDENTIFIER *ROBOT-TEST RUN * AND VERSION NUMBER 1. THE FILE HAS 1 SECTIONS.

FILE IDENTIFICATION PARAMETERS--CSTR1 I.D.CYGRO5 , CSTR1 VERSION 14, CSTR1 DATE 820615, LINK DATE 06/15/82
JOB CARD I.D. IEBK014, USER KOVSC, DATE 82/06/15 , TIME 15.58.43 , MACHINE C

THE CYGRO PROBLEM INCLUDES 3 SEGMENTS (INCLUDING THE PLENUM.) THE LENGTH OF THE ROD IS 108.750

SEGMENT 1 LIES BETWEEN Z = 0.00 AND Z = 45.00

SEGMENT 2 LIES BETWEEN Z = 45.00 AND Z = 100.00

SEGMENT 3 LIES BETWEEN Z = 100.00 AND Z = 108.75

////////////////////////////////////////////////////////////////////////////////////////////////////

CLAD-SHAPE U-DATA VS CURVE FIT

| Z | U-INPUT | U-FIT | U-DIF | V-INPUT | V-FIT | V-DIF |
|---|---|---|---|---|---|---|
| 0.00000 | 0.00000 | .00000 | -.00000 | 0.00000 | .00000 | -.00000 |
| 5.00000 | .00110 | .00110 | .00000 | .00110 | .00110 | .00000 |
| 10.00000 | .00195 | .00195 | .00000 | .00195 | .00195 | .00000 |
| 15.00000 | .00260 | .00260 | -.00000 | .00260 | .00260 | -.00000 |
| 20.00000 | .00300 | .00300 | .00000 | .00300 | .00300 | .00000 |
| 25.00000 | .00290 | .00291 | -.00001 | .00290 | .00291 | -.00001 |
| 30.00000 | .00260 | .00259 | .00001 | .00260 | .00259 | .00001 |
| 35.00000 | .00213 | .00214 | -.00001 | .00213 | .00214 | -.00001 |
| 40.00000 | .00155 | .00155 | .00000 | .00155 | .00155 | .00000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 45.00000 | .00080 | .00079 | .00001 | .00080 | .00079 | .00001 |
| 50.00000 | 0.00000 | .00002 | -.00002 | 0.00000 | .00002 | -.00002 |
| 55.00000 | -.00065 | -.00066 | .00001 | -.00065 | -.00066 | .00001 |
| 60.00000 | -.00121 | -.00121 | -.00000 | -.00121 | -.00121 | -.00000 |
| 65.00000 | -.00165 | -.00164 | -.00001 | -.00165 | -.00164 | -.00001 |
| 70.00000 | -.00190 | -.00191 | .00001 | -.00190 | -.00191 | .00001 |
| 75.00000 | -.00200 | -.00200 | -.00000 | -.00200 | -.00200 | -.00000 |
| 80.00000 | -.00200 | -.00200 | .00000 | -.00200 | -.00200 | .00000 |
| 85.00000 | -.00175 | -.00175 | .00000 | -.00175 | -.00175 | .00000 |
| 90.00000 | -.00135 | -.00135 | .00000 | -.00135 | -.00135 | .00000 |
| 95.00000 | -.00080 | -.00080 | -.00000 | -.00080 | -.00080 | -.00000 |
| 100.00000 | 0.00000 | -.00000 | .00000 | 0.00000 | -.00000 | .00000 |

KTIME 3 TIME 366400+01

| Z-CORR | U(Z) | V(Z) |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| 25.0000 | 2.0912 | 2.0912 |
| 50.0000 | 16.0046 | 16.0046 |
| 75.0000 | 5.3824 | 5.3824 |
| 100.0000 | 4.4292 | 4.4292 |

KTIME 49 TIME 504866+02

| Z-CORR | U(Z) | V(Z) |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| 25.0000 | 2.1539 | 2.1539 |
| 50.0000 | 16.0094 | 16.0094 |
| 75.0000 | 5 4100 | 5.4100 |
| 100.0000 | 4 5107 | 4.5107 |

KTIME 101 TIME 100687+03

| Z-CORR | U(Z) | V(Z) |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| 25.0000 | 2.2379 | 2.2379 |
| 50.0000 | 16.1020 | 16.1020 |
| 75.0000 | 5.4325 | 5.4325 |
| 100.0000 | 4.5858 | 4.5858 |

SUMMARY OF ENVIRONMENTAL DATA AND DEFLECTIONS. ENVIRONMENTAL DATA IS FOR CYGRO CROSS-SECTION 1

| TIME | P-SYS | T-WAT | POWER | Z= | 0.0000 | | 25.0000 | | 50.0000 | | 75.0000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | U(Z) | V(Z) | U(Z) | V(Z) | U(Z) | V(Z) | U(Z) | V(Z) |
| .0000 | 0.0 | 72.0 | 0. | ..... | 0.00000 | 0.00000 | 1.60610 | 1.60610 | 12.18371 | 12.18371 | 5.34712 | 5.34712 |
| .0100 | 0.0 | 78.0 | 0. | ..... | 0.00000 | 0.00000 | 1.59930 | 1.59930 | 12.13552 | 12.13552 | 5.33411 | 5.33411 |
| 3.6640 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09118 | 2.09118 | 16.00463 | 16.00463 | 5.38243 | 5.38243 |
| 7.0439 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.08137 | 2.08137 | 15.88107 | 15.88107 | 5.39068 | 5.39068 |
| 8.0093 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.08337 | 2.08337 | 15.88755 | 15.88755 | 5.39120 | 5.39120 |
| 8.9747 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.08530 | 2.08530 | 15.89346 | 15.89346 | 5.39167 | 5.39167 |
| 9.9401 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.08716 | 2.08716 | 15.89874 | 15.89874 | 5.39213 | 5.39213 |
| 10.9055 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.08896 | 2.08896 | 15.90355 | 15.90355 | 5.39258 | 5.39258 |
| 11.8709 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09072 | 2.09072 | 15.90799 | 15.90799 | 5.39303 | 5.39303 |
| 12.8363 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09244 | 2.09244 | 15.91212 | 15.91212 | 5.39347 | 5.39347 |
| 13.8017 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09413 | 2.09413 | 15.91600 | 15.91600 | 5.39390 | 5.39390 |
| 14.7671 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09580 | 2.09580 | 15.91969 | 15.91969 | 5.39434 | 5.39434 |
| 15.7325 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09746 | 2.09746 | 15.92320 | 15.92320 | 5.39476 | 5.39476 |
| 16.6978 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.09909 | 2.09909 | 15.92656 | 15.92656 | 5.39519 | 5.39519 |
| 17.6632 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10072 | 2.10072 | 15.92980 | 15.92980 | 5.39562 | 5.39562 |
| 18.6286 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10233 | 2.10233 | 15.93293 | 15.93293 | 5.39604 | 5.39604 |
| 19.5940 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10394 | 2.10394 | 15.93595 | 15.93595 | 5.39647 | 5.39647 |
| 20.5594 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10553 | 2.10553 | 15.93888 | 15.93888 | 5.39689 | 5.39689 |
| 21.5248 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10712 | 2.10712 | 15.94174 | 15.94174 | 5.39731 | 5.39731 |
| 22.4902 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.10870 | 2.10870 | 15.94452 | 15.94452 | 5.39773 | 5.39773 |
| 23.4556 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11028 | 2.11028 | 15.94724 | 15.94724 | 5.39815 | 5.39815 |
| 24.4210 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11185 | 2.11185 | 15.94989 | 15.94989 | 5.39858 | 5.39858 |
| 25.3864 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11342 | 2.11342 | 15.95250 | 15.95250 | 5.39900 | 5.39900 |
| 26.3518 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11499 | 2.11499 | 15.95505 | 15.95505 | 5.39942 | 5.39942 |
| 27.3172 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11655 | 2.11655 | 15.95755 | 15.95755 | 5.39984 | 5.39984 |
| 28.2826 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11811 | 2.11811 | 15.96001 | 15.96001 | 5.40026 | 5.40026 |
| 29.2480 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.11967 | 2.11967 | 15.96244 | 15.96244 | 5.40068 | 5.40068 |
| 30.2133 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12123 | 2.12123 | 15.96482 | 15.96482 | 5.40110 | 5.40110 |
| 31.1787 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12278 | 2.12278 | 15.96718 | 15.96718 | 5.40152 | 5.40152 |
| 32.1441 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12433 | 2.12433 | 15.96949 | 15.96949 | 5.40194 | 5.40194 |
| 33.1095 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12589 | 2.12589 | 15.97178 | 15.97178 | 5.40236 | 5.40236 |
| 34.0749 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12744 | 2.12744 | 15.97405 | 15.97405 | 5.40278 | 5.40278 |
| 35.0403 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.12899 | 2.12899 | 15.97628 | 15.97628 | 5.40320 | 5.40320 |
| 36.0057 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13054 | 2.13054 | 15.97849 | 15.97849 | 5.40362 | 5.40362 |
| 36.9711 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13209 | 2.13209 | 15.98068 | 15.98068 | 5.40404 | 5.40404 |
| 37.9365 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13365 | 2.13365 | 15.98284 | 15.98284 | 5.40446 | 5.40446 |
| 38.9019 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13520 | 2.13520 | 15.98499 | 15.98499 | 5.40488 | 5.40488 |
| 39.8673 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13675 | 2.13675 | 15.98711 | 15.98711 | 5.40530 | 5.40530 |
| 40.8327 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13830 | 2.13830 | 15.98921 | 15.98921 | 5.40573 | 5.40573 |
| 41.7981 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.13986 | 2.13986 | 15.99130 | 15.99130 | 5.40615 | 5.40615 |
| 42.7635 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14141 | 2.14141 | 15.99337 | 15.99337 | 5.40657 | 5.40657 |
| 43.7288 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14297 | 2.14297 | 15.99543 | 15.99543 | 5.40699 | 5.40699 |
| 44.6942 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14453 | 2.14453 | 15.99746 | 15.99746 | 5.40742 | 5.40742 |
| 45.6596 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14608 | 2.14608 | 15.99949 | 15.99949 | 5.40784 | 5.40784 |
| 46.6250 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14764 | 2.14764 | 16.00150 | 16.00150 | 5.40826 | 5.40826 |
| 47.5904 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.14920 | 2.14920 | 16.00350 | 16.00350 | 5.40869 | 5.40869 |
| 48.5558 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15077 | 2.15077 | 16.00548 | 16.00548 | 5.40911 | 5.40911 |
| 49.5212 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15233 | 2.15233 | 16.00745 | 16.00745 | 5.40954 | 5.40954 |
| 50.4866 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15390 | 2.15390 | 16.00941 | 16.00941 | 5.40996 | 5.40996 |
| 51.4520 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15546 | 2.15546 | 16.01136 | 16.01136 | 5.41039 | 5.41039 |
| 52.4174 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15703 | 2.15703 | 16.01330 | 16.01330 | 5.41082 | 5.41082 |
| 53.3828 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.15860 | 2.15860 | 16.01523 | 16.01523 | 5.41124 | 5.41124 |
| 54.3482 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16018 | 2.16018 | 16.01715 | 16.01715 | 5.41167 | 5.41167 |
| 55.3136 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16175 | 2.16175 | 16.01906 | 16.01906 | 5.41210 | 5.41210 |

| TIME | P-SYS | T-WAT | POWER | Z= | 0.0000 | | 25.0000 | | 50.0000 | | 75.0000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56.2790 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16333 | 2.16333 | 16.02096 | 16.02096 | 5.41253 | 5.41253 |
| 57.2444 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16491 | 2.16491 | 16.02286 | 16.02286 | 5.41296 | 5.41296 |
| 58.2097 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16649 | 2.16649 | 16.02474 | 16.02474 | 5.41339 | 5.41339 |
| 59.1751 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16807 | 2.16807 | 16.02662 | 16.02662 | 5.41382 | 5.41382 |
| 60.1405 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.16965 | 2.16965 | 16.02848 | 16.02848 | 5.41425 | 5.41425 |
| 61.1059 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17124 | 2.17124 | 16.03035 | 16.03035 | 5.41468 | 5.41468 |
| 62.0713 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17283 | 2.17283 | 16.03220 | 16.03220 | 5.41511 | 5.41511 |
| 63.0367 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17442 | 2.17442 | 16.03405 | 16.03405 | 5.41554 | 5.41554 |
| 64.0021 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17602 | 2.17602 | 16.03589 | 16.03589 | 5.41597 | 5.41597 |
| 64.9675 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17762 | 2.17762 | 16.03772 | 16.03772 | 5.41641 | 5.41641 |
| 65.9329 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.17922 | 2.17922 | 16.03955 | 16.03955 | 5.41684 | 5.41684 |
| 66.8983 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18082 | 2.18082 | 16.04137 | 16.04137 | 5.41728 | 5.41728 |
| 67.8637 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18242 | 2.18242 | 16.04319 | 16.04319 | 5.41771 | 5.41771 |
| 68.8291 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18403 | 2.18403 | 16.04500 | 16.04500 | 5.41815 | 5.41815 |
| 69.7945 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18564 | 2.18564 | 16.04681 | 16.04681 | 5.41858 | 5.41858 |
| 70.7599 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18725 | 2.18725 | 16.04861 | 16.04861 | 5.41902 | 5.41902 |
| 71.7252 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.18887 | 2.18887 | 16.05041 | 16.05041 | 5.41946 | 5.41946 |
| 72.6906 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19049 | 2.19049 | 16.05220 | 16.05220 | 5.41989 | 5.41989 |
| 73.6560 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19211 | 2.19211 | 16.05399 | 16.05399 | 5.42033 | 5.42033 |
| 74.6214 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19373 | 2.19373 | 16.05577 | 16.05577 | 5.42077 | 5.42077 |
| 75.5868 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19536 | 2.19536 | 16.05755 | 16.05755 | 5.42121 | 5.42121 |
| 76.5522 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19699 | 2.19699 | 16.05932 | 16.05932 | 5.42165 | 5.42165 |
| 77.5176 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.19862 | 2.19862 | 16.06109 | 16.06109 | 5.42209 | 5.42209 |
| 78.4830 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20026 | 2.20026 | 16.06286 | 16.06286 | 5.42254 | 5.42254 |
| 79.4484 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20190 | 2.20190 | 16.06462 | 16.06462 | 5.42298 | 5.42298 |
| 80.4138 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20354 | 2.20354 | 16.06638 | 16.06638 | 5.42342 | 5.42342 |
| 81.3792 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20519 | 2.20519 | 16.06814 | 16.06814 | 5.42387 | 5.42387 |
| 82.3446 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20683 | 2.20683 | 16.06989 | 16.06989 | 5.42431 | 5.42431 |
| 83.3100 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.20848 | 2.20848 | 16.07164 | 16.07164 | 5.42476 | 5.42476 |
| 84.2754 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21014 | 2.21014 | 16.07339 | 16.07339 | 5.42520 | 5.42520 |
| 85.2407 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21180 | 2.21180 | 16.07513 | 16.07513 | 5.42565 | 5.42565 |
| 86.2061 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21346 | 2.21346 | 16.07687 | 16.07687 | 5.42610 | 5.42610 |
| 87.1715 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21512 | 2.21512 | 16.07861 | 16.07861 | 5.42654 | 5.42654 |
| 88.1369 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21679 | 2.21679 | 16.08034 | 16.08034 | 5.42699 | 5.42699 |
| 89.1023 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.21846 | 2.21846 | 16.08208 | 16.08208 | 5.42744 | 5.42744 |
| 90.0677 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22013 | 2.22013 | 16.08381 | 16.08381 | 5.42789 | 5.42789 |
| 91.0331 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22181 | 2.22181 | 16.08553 | 16.08553 | 5.42834 | 5.42834 |
| 91.9985 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22349 | 2.22349 | 16.08726 | 16.08726 | 5.42880 | 5.42880 |
| 92.9639 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22518 | 2.22518 | 16.08898 | 16.08898 | 5.42925 | 5.42925 |
| 93.9293 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22686 | 2.22686 | 16.09070 | 16.09070 | 5.42970 | 5.42970 |
| 94.8947 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.22856 | 2.22856 | 16.09242 | 16.09242 | 5.43015 | 5.43015 |
| 95.8601 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23025 | 2.23025 | 16.09414 | 16.09414 | 5.43061 | 5.43061 |
| 96.8255 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23195 | 2.23195 | 16.09585 | 16.09585 | 5.43106 | 5.43106 |
| 97.7909 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23365 | 2.23365 | 16.09757 | 16.09757 | 5.43152 | 5.43152 |
| 98.7562 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23536 | 2.23536 | 16.09928 | 16.09928 | 5.43198 | 5.43198 |
| 99.7216 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23707 | 2.23707 | 16.10099 | 16.10099 | 5.43244 | 5.43244 |
| 100.6870 | 2000.0 | 653.6 | .39E+03 | ..... | 0.00000 | 0.00000 | 2.23788 | 2.23788 | 16.10196 | 16.10196 | 5.43249 | 5.43249 |

SUMMARY OF ENVIRONMENTAL DATA AND DEFLECTIONS. ENVIRONMENTAL DATA IS FOR CYGRO CROSS-SECTION 1

| TIME | P-SYS | T-WAT | POWER | Z= | 100.0000 | |
|---|---|---|---|---|---|---|
| | | | | | U(Z) | V(Z) |
| .0000 | 0.0 | 72.0 | 0. | ..... | 4.74734 | 4.74734 |
| .0100 | 0.0 | 78.0 | 0. | ..... | 4.73736 | 4.73736 |
| 3.6640 | 2000.0 | 653.6 | .39E+03 | ..... | 4.42923 | 4.42923 |
| 7.0439 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45063 | 4.45063 |
| 8.0093 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45159 | 4.45159 |
| 8.9747 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45259 | 4.45259 |
| 9.9401 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45365 | 4.45365 |
| 10.9055 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45476 | 4.45476 |
| 11.8709 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45592 | 4.45592 |
| 12.8363 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45710 | 4.45710 |
| 13.8017 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45832 | 4.45832 |
| 14.7671 | 2000.0 | 653.6 | .39E+03 | ..... | 4.45956 | 4.45956 |
| 15.7325 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46082 | 4.46082 |
| 16.6978 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46209 | 4.46209 |
| 17.6632 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46338 | 4.46338 |
| 18.6286 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46468 | 4.46468 |
| 19.5940 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46599 | 4.46599 |
| 20.5594 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46732 | 4.46732 |
| 21.5248 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46865 | 4.46865 |
| 22.4902 | 2000.0 | 653.6 | .39E+03 | ..... | 4.46999 | 4.46999 |
| 23.4556 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47134 | 4.47134 |
| 24.4210 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47270 | 4.47270 |
| 25.3864 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47406 | 4.47406 |
| 26.3518 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47543 | 4.47543 |
| 27.3172 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47680 | 4.47680 |
| 28.2826 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47818 | 4.47818 |
| 29.2480 | 2000.0 | 653.6 | .39E+03 | ..... | 4.47957 | 4.47957 |
| 30.2133 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48095 | 4.48095 |
| 31.1787 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48235 | 4.48235 |
| 32.1441 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48374 | 4.48374 |
| 33.1095 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48514 | 4.48514 |
| 34.0749 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48654 | 4.48654 |
| 35.0403 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48794 | 4.48794 |
| 36.0057 | 2000.0 | 653.6 | .39E+03 | ..... | 4.48935 | 4.48935 |
| 36.9711 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49076 | 4.49076 |
| 37.9365 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49217 | 4.49217 |
| 38.9019 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49359 | 4.49359 |
| 39.8673 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49500 | 4.49500 |
| 40.8327 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49642 | 4.49642 |
| 41.7981 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49784 | 4.49784 |
| 42.7635 | 2000.0 | 653.6 | .39E+03 | ..... | 4.49927 | 4.49927 |
| 43.7288 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50069 | 4.50069 |
| 44.6942 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50212 | 4.50212 |
| 45.6596 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50354 | 4.50354 |
| 46.6250 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50497 | 4.50497 |
| 47.5904 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50640 | 4.50640 |
| 48.5558 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50783 | 4.50783 |
| 49.5212 | 2000.0 | 653.6 | .39E+03 | ..... | 4.50927 | 4.50927 |
| 50.4866 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51070 | 4.51070 |
| 51.4520 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51214 | 4.51214 |
| 52.4174 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51357 | 4.51357 |
| 53.3828 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51501 | 4.51501 |
| 54.3482 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51645 | 4.51645 |
| 55.3136 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51789 | 4.51789 |

| TIME | P-SYS | T-WAT | POWER | Z= | 100.0000 | |
|---|---|---|---|---|---|---|
| 56.2790 | 2000.0 | 653.6 | .39E+03 | ..... | 4.51933 | 4.51933 |
| 57.2444 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52077 | 4.52077 |
| 58.2097 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52221 | 4.52221 |
| 59.1751 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52366 | 4.52366 |
| 60.1405 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52510 | 4.52510 |
| 61.1059 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52654 | 4.52654 |
| 62.0713 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52799 | 4.52799 |
| 63.0367 | 2000.0 | 653.6 | .39E+03 | ..... | 4.52944 | 4.52944 |
| 64.0021 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53088 | 4.53088 |
| 64.9675 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53233 | 4.53233 |
| 65.9329 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53378 | 4.53378 |
| 66.8983 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53523 | 4.53523 |
| 67.8637 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53667 | 4.53667 |
| 68.8291 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53812 | 4.53812 |
| 69.7945 | 2000.0 | 653.6 | .39E+03 | ..... | 4.53957 | 4.53957 |
| 70.7599 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54102 | 4.54102 |
| 71.7252 | 2000.0 | 653.6 | .39E+03 | .... | 4.54247 | 4.54247 |
| 72.6906 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54393 | 4.54393 |
| 73.6560 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54538 | 4.54538 |
| 74.6214 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54683 | 4.54683 |
| 75.5868 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54828 | 4.54828 |
| 76.5522 | 2000.0 | 653.6 | .39E+03 | ..... | 4.54974 | 4.54974 |
| 77.5176 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55119 | 4.55119 |
| 78.4830 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55264 | 4.55264 |
| 79.4484 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55410 | 4.55410 |
| 80.4138 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55555 | 4.55555 |
| 81.3792 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55701 | 4.55701 |
| 82.3446 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55846 | 4.55846 |
| 83.3100 | 2000.0 | 653.6 | .39E+03 | ..... | 4.55992 | 4.55992 |
| 84.2754 | 2000.0 | 653.6 | .39E+03 | ..... | 4.56137 | 4.56137 |
| 85.2407 | 2000.0 | 653.6 | .39E+03 | ..... | 4.56283 | 4.56283 |
| 86.2061 | 2000.0 | 653.6 | .39E+03 | ..... | 4.56428 | 4.56428 |
| 87.1715 | 2000.0 | 653.6 | .39E+03 | .... | 4.56574 | 4.56574 |
| 88.1369 | 2000.0 | 653.6 | .39E+03 | .... | 4.56720 | 4.56720 |
| 89.1023 | 2000.0 | 653.6 | .39E+03 | ..... | 4.56865 | 4.56865 |
| 90.0677 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57011 | 4.57011 |
| 91.0331 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57157 | 4.57157 |
| 91.9985 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57302 | 4.57302 |
| 92.9639 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57448 | 4.57448 |
| 93.9293 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57594 | 4.57594 |
| 94.8947 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57740 | 4.57740 |
| 95.8601 | 2000.0 | 653.6 | .39E+03 | ..... | 4.57886 | 4.57886 |
| 96.8255 | 2000.0 | 653.6 | .39E+03 | ..... | 4.58031 | 4.58031 |
| 97.7909 | 2000.0 | 653.6 | .39E+03 | ..... | 4.58177 | 4.58177 |
| 98.7562 | 2000.0 | 653.6 | .39E+03 | ..... | 4.58323 | 4.58323 |
| 99.7216 | 2000.0 | 653.6 | .39E+03 | ..... | 4.58469 | 4.58469 |
| 100.6870 | 2000.0 | 653.6 | .39E+03 | ..... | 4.58576 | 4.58576 |

END OF LIFE FREE SHAPE

| AXIAL COOR | U(Z) | V(Z) |
|---|---|---|
| NODE POINT | 1 | |
| 0.00 | 0.0000 | 0.0000 |
| 2.00 | -.0126 | -.0126 |
| 4.00 | -.0781 | -.0781 |
| 6.00 | -.1710 | -.1710 |
| NODE POINT | 2 | |
| 6.67 | -.2036 | -.2036 |
| 8.67 | -.3020 | -.3020 |
| 10.67 | -.3910 | -.3910 |
| 12.67 | -.4532 | -.4532 |
| NODE POINT | 3 | |
| 13.33 | -.4650 | -.4650 |
| 15.33 | -.4700 | -.4700 |
| 17.33 | -.3620 | -.3620 |
| 19.33 | -.0384 | -.0384 |
| NODE POINT | 4 | |
| 20.00 | .1351 | .1351 |
| 22.00 | .8283 | .8283 |
| 24.00 | 1.7262 | 1.7262 |
| 26.00 | 2.7882 | 2.7882 |
| 28.00 | 3.9732 | 3.9732 |
| 30.00 | 5.2404 | 5.2404 |
| 32.00 | 6.5489 | 6.5489 |
| 34.00 | 7.8578 | 7.8578 |
| NODE POINT | 5 | |
| 35.00 | 8.4997 | 8.4997 |
| 37.00 | 9.7932 | 9.7932 |
| 39.00 | 11.0945 | 11.0945 |
| 41.00 | 12.3448 | 12.3448 |
| 43.00 | 13.4856 | 13.4856 |
| 45.00 | 14.4585 | 14.4585 |
| 47.00 | 15.2047 | 15.2047 |
| 49.00 | 15.6659 | 15.6659 |
| NODE POINT | 6 | |
| 50.00 | 15.7712 | 15.7712 |
| 52.00 | 15.7139 | 15.7139 |
| 54.00 | 15.3422 | 15.3422 |
| 56.00 | 14.7158 | 14.7158 |
| 58.00 | 13.8944 | 13.8944 |
| 60.00 | 12.9377 | 12.9377 |
| 62.00 | 11.9053 | 11.9053 |
| 64.00 | 10.8571 | 10.8571 |
| NODE POINT | 7 | |
| 65.00 | 10.3456 | 10.3456 |
| 67.00 | 9.3130 | 9.3130 |
| 69.00 | 8.2648 | 8.2648 |
| 71.00 | 7.2551 | 7.2551 |
| 73.00 | 6.3376 | 6.3376 |
| 75.00 | 5.5662 | 5.5662 |
| 77.00 | 4.9949 | 4.9949 |
| 79.00 | 4.6774 | 4.6774 |
| NODE POINT | 8 | |
| 80.00 | 4.6307 | 4.6307 |
| 82.00 | 4.6200 | 4.6200 |
| 84.00 | 4.6115 | 4.6115 |

| | | |
|---|---|---|
| 86.00 | 4.6050 | 4.6050 |
| NODE POINT 9 | | |
| 86.67 | 4.6031 | 4.6031 |
| 88.67 | 4.5984 | 4.5984 |
| 90.67 | 4.5947 | 4.5947 |
| 92.67 | 4.5919 | 4.5919 |
| NODE POINT 10 | | |
| 93.33 | 4.5911 | 4.5911 |
| 95.33 | 4.5891 | 4.5891 |
| 97.33 | 4.5875 | 4.5875 |
| 99.33 | 4.5862 | 4.5862 |
| NODE POINT 11 | | |

References

1. J. B. Newman and S. E. Kovscek, "The CYGRO5 Fuel Rod Analysis Computer Program," WAPD-TM-1504, October, 1982.

2. S. E. Martin, "A Finite Element Procedure for Calculating the Three-Dimensional Inelastic Bowing of Fuel Rods," WAPD-TM-1498, May 1982.

3. J. B. Newman, "Inelastic Analysis of Bowing in Multispan Fuel Rods Subjected to Axial Thrust," Nuclear Engineering and Design, 9, 81-104 (1969).

4. J. J. Urbaniak, "ROBOT - A Computer Program to Solve the Bowing Problem in Rod-Type Fuel Elements," WAPD-TM-847, July 1969.

5. W. R. Cadwell, Ed., "Reference Manual - Bettis Programming Environment," WAPD-TM-1181, September 1974.

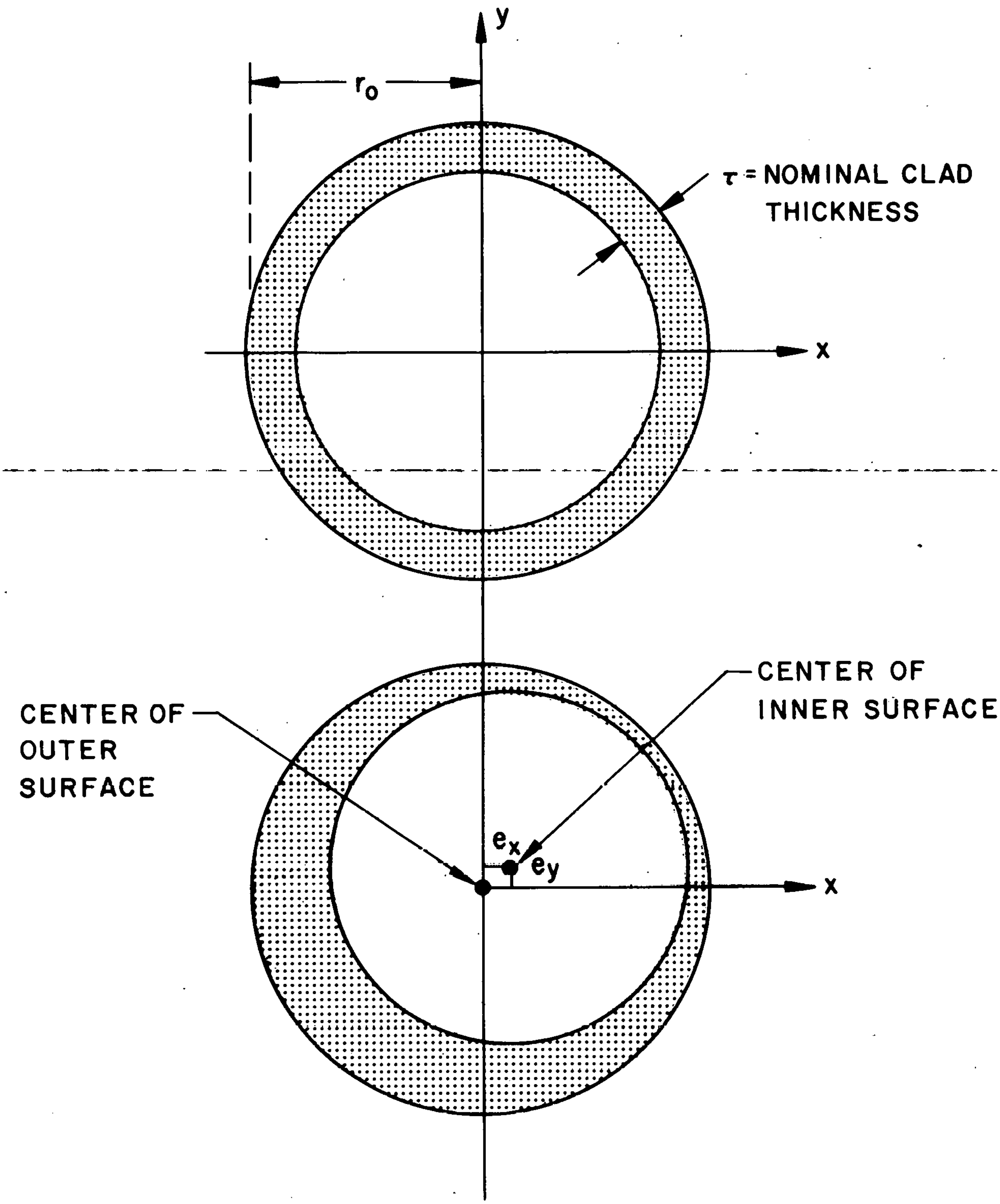



FIGURE 1. CLADDING ECCENTRICITY

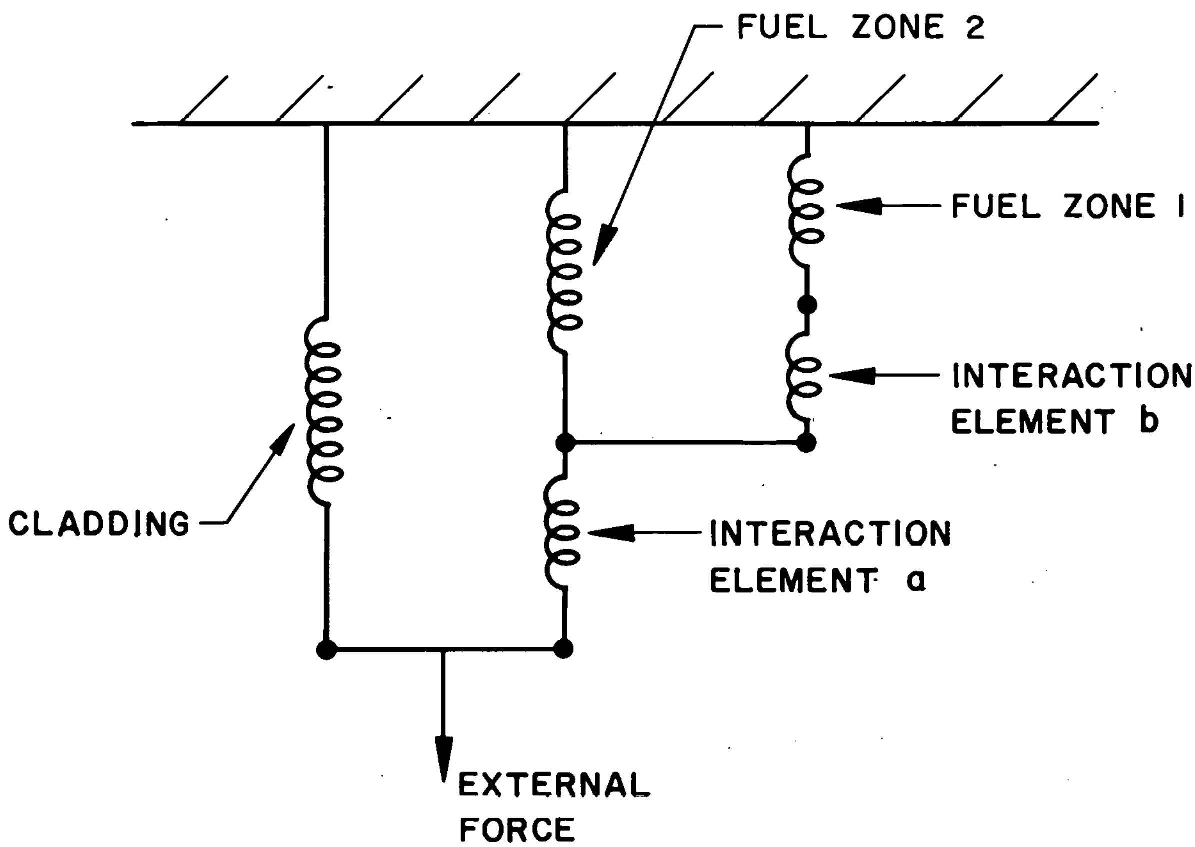



FIGURE 2. LINEAR SPRING ANALOG OF THE INTERACTION MODEL

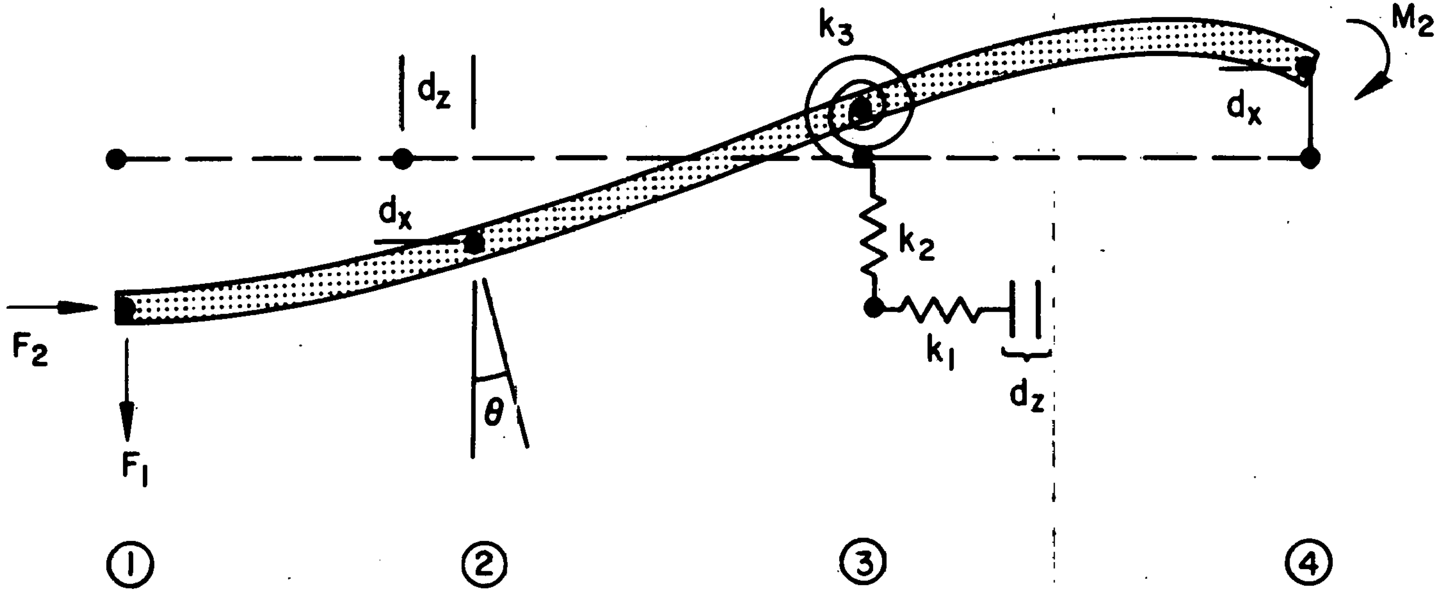



FIGURE 3. BOUNDARY CONDITION TYPES

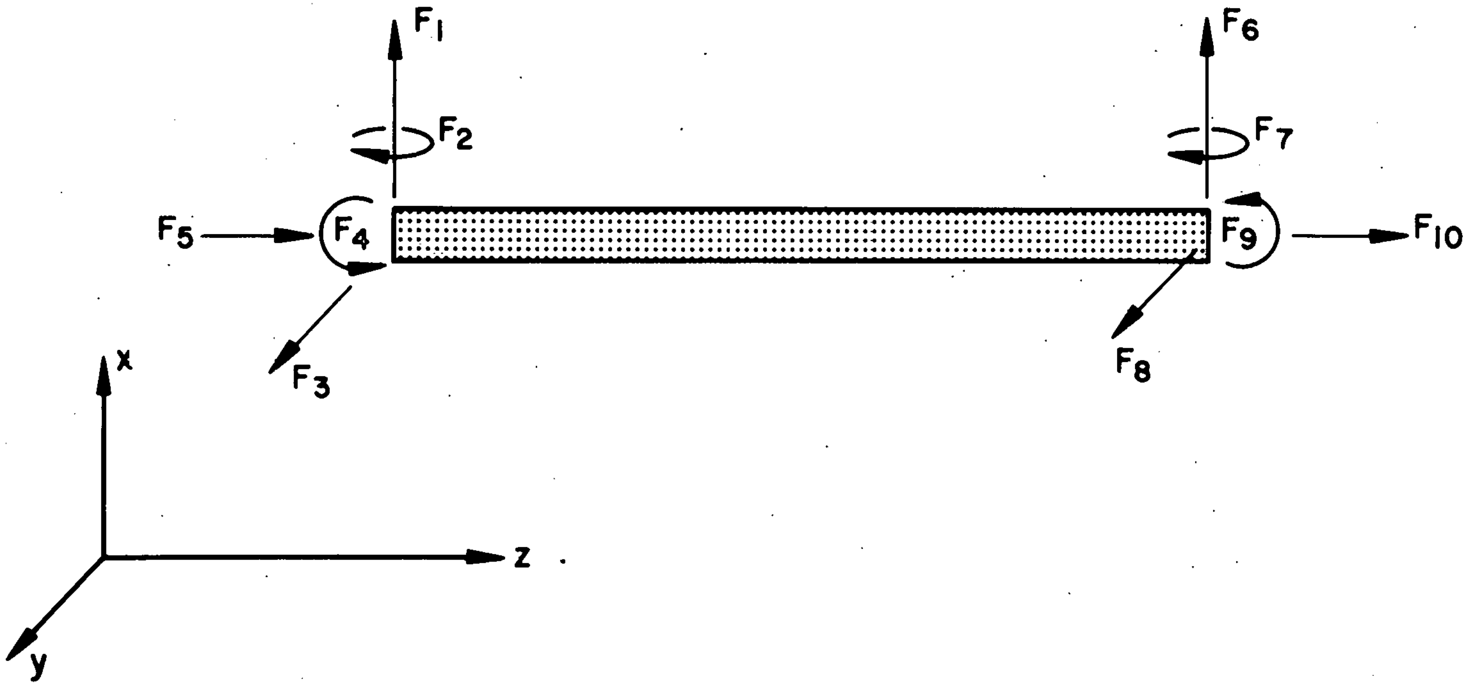
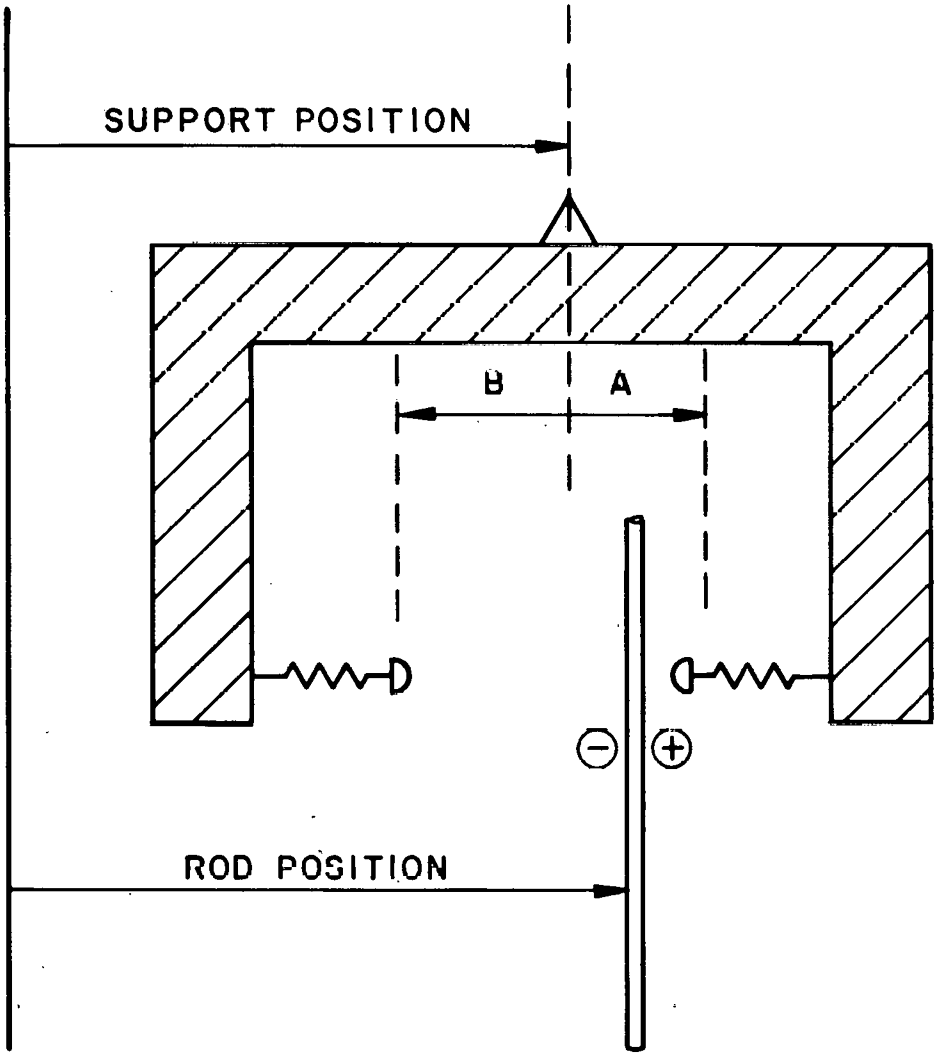



FIGURE 4. EXTERNAL FORCES AND MOMENTS APPLIED TO ENDS OF BEAM ELEMENT




A – FREE POSITION OF POSITIVE SPRING
B FREE POSITION OF NEGATIVE SPRING

FIGURE 5. FLEXIBLE SUPPORT CONFIGURATION

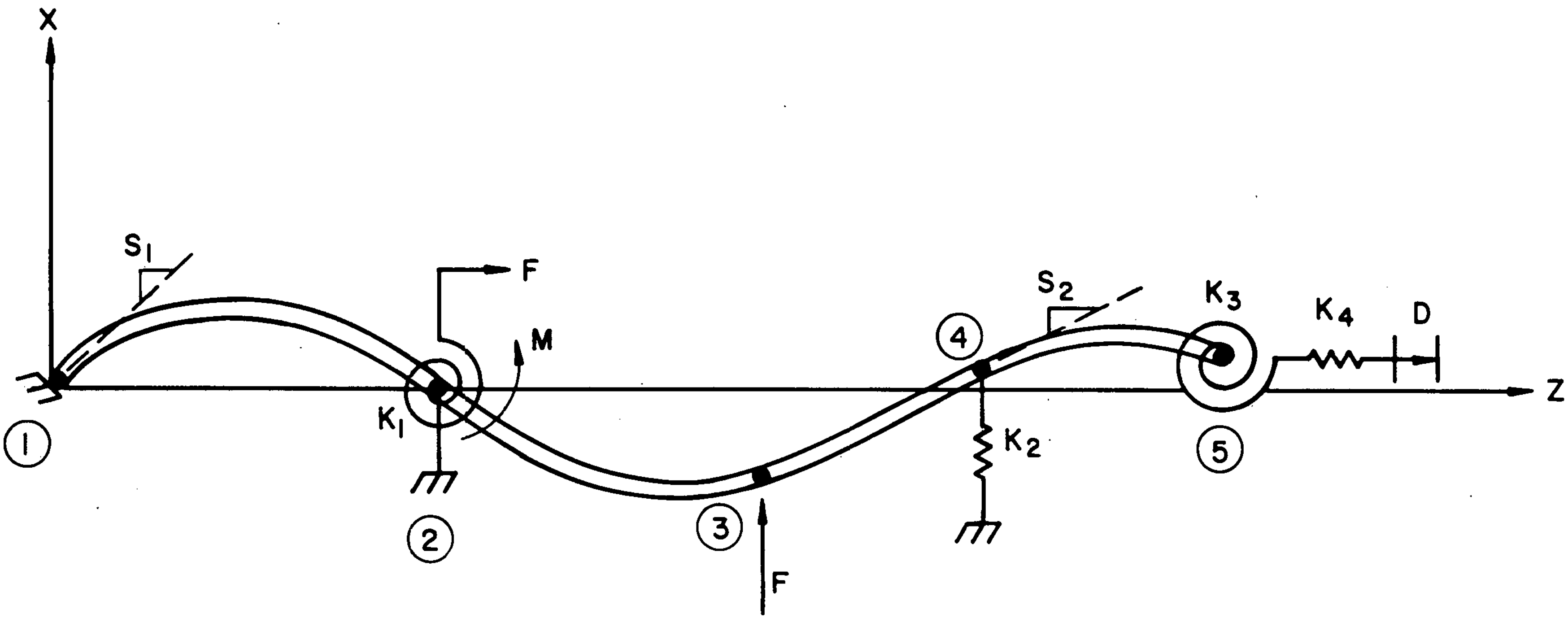



FIGURE 6. BOUNDARY CONDITIONS FOR SAMPLE PROBLEM

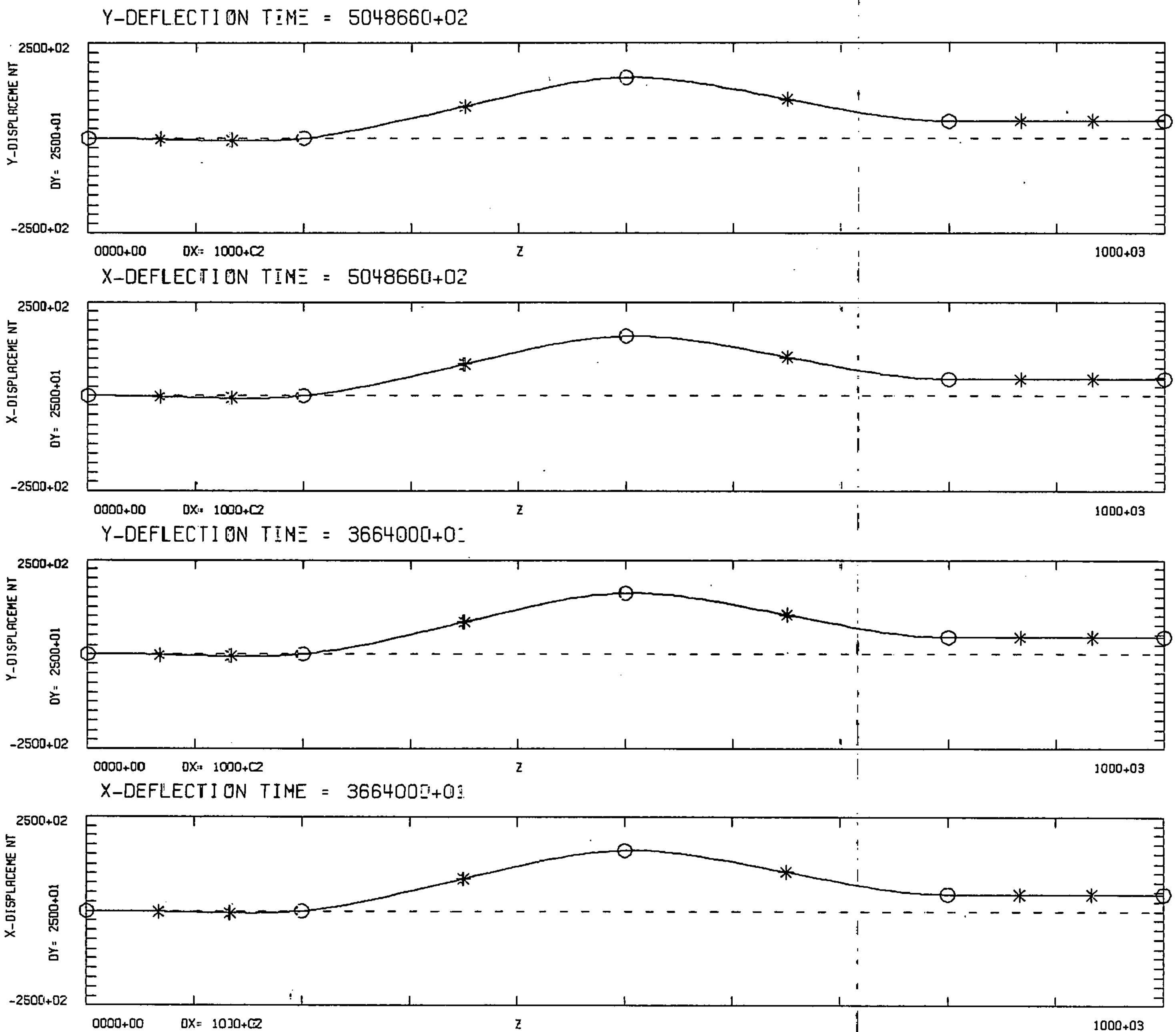



FIGURE 7. ROECT3-Generated Deflection Plots

APPENDIX: ROBOT3 Computer Program Abstract

1. Program Name (and) Title: ROBOT3

2. Computer and Language(s): CDC-7600, FORTRAN IV and Compass

3. Problem Solved: ROBOT3 (Reference [a]) has been developed from ROBOT (Reference [b]) and the finite element procedure for calculating the three-dimensional inelastic bowing of fuel rods described in Reference [c]. The fuel rod is modeled as a viscoelastic beam whose material properties are derived as perturbations of the results of an axisymmetric stress analysis of the fuel rod. The effects which are taken into account in calculating the rod's lateral bowing include (1) initial curvature, (2) lateral, axial, and rotational motions and forces at the rod supports, (3) transverse gradients of temperature, fast-neutron flux, and fissioning rate, and (4) cladding circumferential wall thickness variation.

4. Method Solution: There are two main calculational parts. One is the formulation of the rod's constitutive equations (i.e. the moment-curvature and axial force-strain relations). The second is the calculation of the rod's deflection increments using the finite element method. For a given rod geometry and operational history, the CYGRO5 computer program (Reference [d]) is used to obtain a data file which contains histories of material properties and axisymmetric stresses and strains in the fuel rod. This data is used to calculate some of the terms in the constitutive equations. Additional terms in these equations correspond to moment-free curvatures induced by transverse gradients of temperature and fast-neutron flux and by cladding circumferential wall thickness variation. These induced curvatures are calculated using material property models borrowed from the CYGRO5 program. The constitutive equations for each of the fuel zones and the cladding are then calculated using the CYGRO5 data file and the induced curvatures. An interaction model is used to combine these equations into a set of equations which characterize the behavior of the fuel rod as a whole.

Once the constitutive equations for the fuel rod have been defined for a timestep, the incremental finite element equations are formulated. The finite element formulation is nonlinear because of the coupling between the axial extension and lateral deflection. The rod supports are modeled by specifying either force, displacement, or flexible boundary conditions. The finite element formulation results in a symmetric and narrowly banded structure stiffness matrix which is solved using a Cholesky-type equation solver (Reference [e]).

5. Restrictions on the Complexity of the Problem: A maximum of 99 support locations may be specified. The number of elements is limited by the available central memory storage since the element related data is dynamically allocated. Fuel rods containing either single zone or duplex fuel may be analyzed. Simplex fuel has an annular or cylindrical fuel pellets consisting of one material. With duplex fuel, the fuel pellet is generally made of two materials - an annular or cylindrical pellet consisting of one material surrounded by an annular pellet made of another material. Duplex fuel is currently under development for use in water breeder reactors.

6. Related and Auxiliary Programs: The rod geometry, operating history, material properties and the histories of axisymmetric stresses and strains are obtained from a file generated by CYGRO5. ROBOT3 uses Bettis programming environmental routines (Reference [f]) such as CARDS for input and FMG for reading the data file generated by CYGRO5. The environmental routines are available with the ROBOT3 program upon request.

7. Typical Running Time: The running time depends on the number of history timesteps defined in the CYGRO5 data file and the number of elements defined in problem input. The program uses .04 seconds per element for each timestep on a CDC-7600.

8. Machine Requirements: CDC-7600 with 140K of central memory and an LCM requirement of 2K + 4K per CYGRO segment plus 2.5K per element.

9. Operating System: CDC-7600 Scope 2.0

10. Availability: Reference [a] is available from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22151

Copies of the computer program may be obtained by domestic users from

Argonne Code Center
Attention: Mrs. Margaret Butler
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60440

11. References:

a. S. E. Kovscek and S. E. Martin, "ROBOT3 - A Computer Program to Calculate the In-Pile Three-Dimensional Bowing of Cylindrical Fuel Rods", WAPD-TM-1527.

b. J. J. Urbaniak, "ROBOT - A Computer Program to Solve the Bowing Problem in Rod-Type Fuel Elements, "WAPD-TM-847, July 1969.

c. S. E. Martin, "A Finite Element Procedure for Calculating the Three-Dimensional Inelastic Bowing of Fuel Rods", WAPD-TM-1498, May 1982.

d. J. B. Newman and S. E. Kovscek, "The CYGRO5 Fuel Rod Analysis Computer Program", WAPD-TM-1504, October, 1982.

e. V. N. Faddeeva, "Computational Methods of Linear Algebra", Dover Publications, New York 1959.

f. W. R. Cadwell, Ed. "Reference Manual - Bettis Programming Environment", WAPD-TM-1181, September 1974.

12. Name and Establishment of Authors:

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