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ACCEPT: A THREE-DIMENSIONAL FINITE ELEMENT PROGRAM FOR LARGE DEFORMATION ELASTIC-PLASTIC-CREEP ANALYSIS OF PRESSURIZED TUBES

(LWBR/AWBA Development Program)

D. N. Hutula (Analyst), B. E. Wiancko (Programmer)

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MARCH 1980

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BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA

Operated for the U. S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

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BETTIS ATOMIC POWER LABORATORY WEST MIFFLIN, PENNSYLVANIA

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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 electrical 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 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 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 is expected to be operated for about 4 to 5 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a 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 program is exploring some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information being 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) are under the technical direction of the Division of Naval Reactors of DOE. They have the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

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

ACCEPT is a three - dimensional finite element computer program for analysis of large - deformation elastic - plastic - creep response of Zircaloy tubes subjected to temperature, surface pressures, and axial force. A twenty - node, tri - quadratic, isoparametric element is used along with a Zircaloy materials model. A linear time - incremental procedure with residual force correction is used to solve for the time - dependent response. The program features an algorithm which automatically chooses the time step sizes to control the accuracy and numerical stability of the solution. A contact - separation capability allows modeling of interaction of reactor fuel rod cladding with fuel pellets or external supports.

ACCEPT: A Three - Dimensional Finite Element Program for Large Deformation Elastic - Plastic - Creep Analysis of Pressurized Tubes

D.N. HUTULA (ANALYST) B.E.WIANCKO (PROGRAMMER)

****
1. INTRODUCTION
****

Structural evaluation of nuclear reactor fuel rod cladding is a demanding task, involving the assurance that structural integrity of the cladding will be maintained over long periods of time under severe loading and environmental conditions. Among the deformational processes which must be evaluated for their possible effects on structural integrity are: deformation of cladding into unsupported axial gaps between fuel pellets or in the plenum region near the end of a rod; development of circumferential ridges and grooves in cladding near the chamfered ends of fuel pellets; and development of axial wrinkles in the cladding as it creeps down and partially contacts the fuel pellets.

Analytical simulaton of such deformational processes requires accurate modeling of the material behavior, accurate modeling of the geometry (including the effects of finite changes in geometry due to deformation), and an effective numerical procedure for solving the mathematical equations of the model. The ACCEPT program was designed to provide such an analysis capability.

This document describes the capabilities, use, and a summary of the theory of the ACCEPT program. Mathematical details of the theory can be found in Reference 1 and in Appendix B of this report, which documents the Zircaloy material behavior model.

The material behavior model, as described in this document, does not include the effects of irradiation on material behavior, so the program should be used for applications in which irradiation effects are unimportant.

****
2. PROGRAM DESCRIPTION
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****
2.1 SUMMARY OF CAPABILITIES
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ACCEPT solves for the elastic-plastic-creep deformation of 3-dimensional Zircaloy tubes subjected to temperature, surface pressures, and axial force. Large deformation theory is used to accurately account for the effects of finite changes in geometry. A Zircaloy materials model is used to predict the anisotropic elastic - plastic - creep material behavior. This model includes elastic, thermal expansion, and thermal creep behavior.

A 20-node, tri-quadratic, isoparametric, 3-dimensional finite element is used in the program. The curved surfaces of this element allow accurate modeling of the geometry of the tube, including such geometrical imperfections as circumferential thickness variations and initial ovality or out - of - roundness.

Options are provided to model the tube such that the cross - section of the middle surface is in the form of an ellipse, an equilateral polygon, or an irregular polygon. In all cases, the finite element mesh is automatically generated from a small number of geometry parameters provided by the user.

A capability is provided for frictionless contact - separation interaction of the inner or outer wall of the tube with one or more rigid surfaces. This capability allows modeling of interaction of reactor fuel rod cladding with fuel pellets or external supports.

A unique feature of the program is an automatic time step control algorithm which chooses the time step sizes to control the accuracy and numerical stability of the solution. This feature makes the solution of large deformation elastic-plastic-creep problems almost routine and allows the user to concentrate on the physical aspects of a problem without being overburdened by the intricacies of the numerical analysis.

A program restart capability allows a problem to be restarted from any of the time steps for which data was stored on the output file. This capability allows long - running problems to be solved in a series of runs, each starting where the previous run terminated. It also allows changing the loading conditions in subsequent runs to permit such things as elastic unloading from selected points in time.

The method of solution of the sets of linear equations formed at each time-step is a direct method known as a "wavefront" method. The MATUS program (Reference 2) also uses a wavefront method, however the implementation of this method in ACCEPT is approximately five times faster than that in MATUS.

A companion program, ACCUSE (ACCEPT USER - SELECTED END - RESULTS) (Section 4), is used to selectively print or plot the results generated by ACCEPT. It is also used to calculate additional output such as nodal point plastic strains, total strains, or stresses. A third program, EDFILE (APPENDIX A), is used to manipulate the data files produced by ACCEPT.

****

2.2 SUMMARY OF THEORY

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The essential concepts of the ACCEPT theory, necessary for a basic understanding of the program, are highlighted in the sections which follow. The mathematical details of the theory are not given here but can be found in Reference 1 and in Appendix B of this document.

****

2.2.1 FINITE ELEMENT

****

The finite element used in ACCEPT is a three-dimensional, twenty-node, tri-quadratic, isoparametric element. This element, an example of which is shown in Figure 2.1, has a node at each of the eight corners and a node at the midpoint of each of the twelve edges. Each node has three degrees of freedom which are the displacements in the coordinate directions of a Cartesian (X, Y, Z) coordinate system. The displacement field within an element is a tri-quadratic function of the curvilinear isoparametric coordinates.*

The isoparametric formulation assures compatibility at interelement boundaries, both before and after deformation. Details of the element formulation can be found in many finite element books, such as Reference 3.

The numerical integration necessary to compute the finite element stiffness matrix is performed in ACCEPT using an eight-point (2X2X2) Gauss rule.**

The curved surfaces and edges of this element permit accurate geometric modeling of tube geometries. The element was developed a number of years ago and has been used extensively in several other three-dimensional finite element programs. There appears to be agreement among the finite element community that this element is, in the current state-of-the-art, the best general purpose three-dimensional element.

*The faces of an element correspond to coordinate surfaces and the edges correspond to coordinate lines of the curvilinear isoparametric coordinate system local to the element. One of the three isoparametric coordinates is equal to plus or minus one on a face.

**The eight integration or Gauss points are the points where each of the isoparametric coordinates is equal to plus or minus SQRT(3)/3.

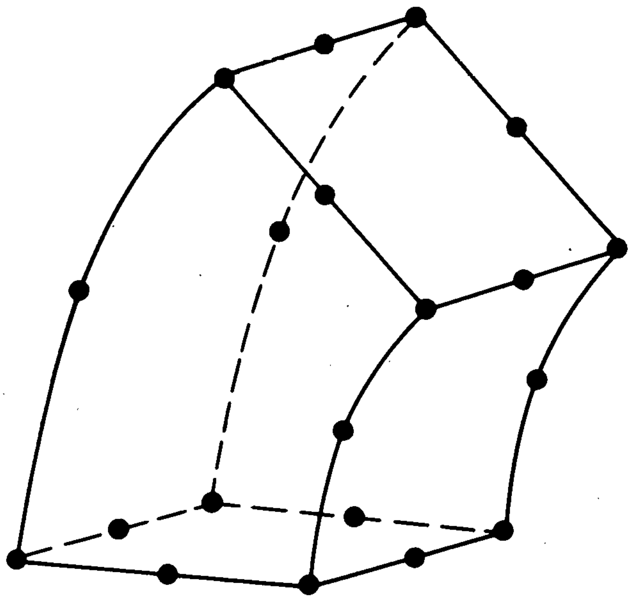


FIGURE 2.1 TWENTY NODE, TRI-QUADRATIC ISOPARAMETRIC FINITE ELEMENT

****
2.2.2 MATERIAL BEHAVIOR
****

The materials model used in ACCEPT was developed over the course of the last several years to model the time dependent elastic-plastic-creep deformation response of Zircaloy subjected to stress, and temperature. Although the model was developed specifically for Zircaloy, it is quite general and possibly would be applicable to other materials, provided, of course, that the material constants involved in the model are given appropriate values based on experimental data for the material.

A brief description of the features of the model is given below. More detail can be found in Appendix B.

The model accounts for the anisotropic nature of the material. The anisotropy is sufficiently significant in Zircaloy to require modeling of its effects to achieve an accurate representation of the deformation behavior.

The stresses and strain rates of the model are referred to an orthogonal set of axes which align with preferred directions of the anisotropic material. In tubing material, these directions, numbered 1, 2, and 3, are the thickness, circumferential, and axial directions, respectively. More will be said later in Section 2.2.3 regarding the definition of the stresses and strain rates and regarding rotation of the orthogonal set of axes.

The total strain rate tensor is assumed to be composed of the sum of an elastic rate, a thermal expansion or growth rate, and a thermal plastic creep rate. These strain rates are discussed below:

1. The elastic strain rate is linearly dependent on the stress rate through a compliance tensor which is temperature dependent. Thus, hypoelastic behavior is assumed.

2. The thermal expansion rate is dependent on temperature and temperature rate.

3. The thermal plastic creep rate is dependent on temperature, stress, and a strain hardening parameter. Both transient and steady-state creep are included in the model.

****
2.2.3 STRESS, STRAIN AND THEIR TIME RATES OF CHANGE
****

The anisotropic material behavior model discussed in the previous section uses an orthogonal set of axes to which the components of the stress and strain rate tensors are referred. These axes, referred to herein as the characteristic axes, align with preferred directions of the anisotropic material.

In a large displacement, large deformation formulation, such as used in ACCEPT, it is necessary to account for the effects of rotation of the characteristic axes as the deformation progresses. In the theory used in ACCEPT, it is postulated that the characteristic axes, at each material point, rotate with an angular velocity corresponding to the spin at the material point.* This postulate allows the development of the equations governing the motion of the characteristic axes. These equations are solved, as part of the ACCEPT solution process, to keep track of the orientation of the characteristic axes throughout the deformation history.

The stress tensor used in the material behavior model is the Cauchy stress tensor, with components referred to the rotating characteristic axes. These stress components are the so-called true stresses which are interpreted as force per unit of current area. The ordinary time derivatives of these stress components form the stress rate tensor used in the material model.**

The strain rate tensor used in the material behavior model is the deformation rate tensor, with components referred to the rotating characteristic axes. These strain rate components correspond to the so-called true strain rates which, in any particular direction, are interpreted as the rate of change of length per unit current length of a material line segment instantaneously parallel to the particular direction. The strain components, which are reported in the program output but are not used directly in the analysis, are the time integrals of the corresponding strain rate components.

*Spin is a field quantity derived from velocity gradients. The spin at a material point can be interpreted as the local angular velocity of the material at that point.

**This stress rate tensor corresponds to the Jaumann stress rate tensor with components referred to the rotating characteristic axes (Reference 4).

****
2.2.4 INCREMENTAL SOLUTION PROCEDURE
****

The large deformation formulation and the nonlinear, history-dependent nature of the material behavior representation necessitate the use of a time-incremental procedure to solve for the deformation history. A linear incremental procedure with residual force correction is used in ACCEPT. This procedure, with appropriate control of the time step sizes, can generate numerically stable and accurate approximations to the true solution.

The finite element equilibrium equations, expressed in terms of nodal displacement and force increments, are developed using the principle of virtual work. In a nonlinear formulation, the principle of virtual work, when expressed in terms of displacement gradient increments, involves these increments in a nonlinear fashion. The nonlinear terms are linearized about the known solution state at the beginning of a time-step in order to obtain a tractable set of equations that can be solved for the nodal displacement and force increments for the time step.

The solution increment thus obtained is not, strictly speaking, the correct increment since it involves an error due to linearization of the governing equations. The error introduced during a time step can be made small by assuring that the neglected nonlinear terms in the governing equations are small compared to the retained linear terms. This is accomplished in the program by a time step control algorithm which is discussed in the next section.

The errors introduced during a series of time steps, if allowed to accumulate and multiply, could seriously degrade the accuracy of the solution. In order to reduce the accumulation of error, a technique known as residual force correction is used. This technique makes use of the stress solution at the beginning of a time step which, due to errors made in previous time steps, is not necessarily in equilibrium with the applied loads. The body forces and surface tractions which would be required to equilibrate the stress solution are termed "residual forces". In the technique, these residual forces calculated at the beginning of a time step are treated as additional forces which are applied during the step. This tends to keep the numerical solution on the right track and reduces the tendency to drift away from the correct solution.

****
2.2.5 TIME STEP CONTROL
****

Time intervals are selected by the user. These intervals are then subdivided into time steps. The time step sizes are automatically controlled by the program, in accordance with a number of parameters specified by the user, as described in Section 3.1.4. The intent of the time step control algorithm is to provide a means by which the accuracy of the solution can be kept within a reasonable level by choosing time step sizes that are small enough to do this, but not so small as to result in excessive running time. This is accomplished by monitoring the progress of the solution and automatically choosing time step sizes to limit the size of the increments in certain variables. Thus, a detailed knowledge of the solution to a particular problem is not required on the part of the user.

The program calculates several "candidate" time step sizes, based on various criteria. The smallest of these candidates is the one actually used. These candidates are printed in the program output in the order described below:

CANDIDATE 1: This candidate is intended to control the accuracy of the integration of the stress-strain rate equations of the material behavior model. The candidate is based on the estimated stress error that was introduced during the previous time step. The stress error, in this context, is defined as the difference between the first and second iterates of a Newton-Raphson iterative solution of the incremental stress-strain relations. This is explained further as follows:

At the beginning of a time step, a linearized relationship between strain increments and stress increments for the time step is established. This relationship is based on a linear Taylor Series expansion about the known stress state at the beginning of the time step. After completion of the time step, the strain increments are calculated from the displacement increments. Using these strain increments, the linearized stress-strain relationship is solved for the stress increments. These stress increments constitute the first iterate of the Newton-Raphson process and permit the calculation of an estimate of the stress state at the middle of the time step. Now, a second linearized relationship is established, based on an expansion about the estimated stress state at the middle of the time step. Using the same strain increments as before, the second linearized relationship is solved for the stress increments which correspond to the second iterate of the Newton-Raphson process. The difference between the first and second iterates is defined as the stress error. The maximum stress error is defined as the maximum absolute value of all components at all integration points.

The candidate time step size for a particular time step is the current best estimate of the time step size that will result in a maximum stress error equal to a user-prescribed desired stress error. The candidate is calculated as the previous time step size multiplied by the square root of the ratio of the desired stress error to the previous maximum stress error.

If, for any time step, the maximum stress error exceeds a user-prescribed maximum allowable stress error, the time step will be repeated using a new (smaller) time step size which is the smallest of all the candidates.

CANDIDATE 2: This candidate is intended to control the magnitude of the maximum displacement gradient increment. In the linearization of the governing equations (see Section 2.1.4), the higher order terms involving the displacement gradient increments are neglected. In order for this to result in a reasonably small error, the displacement gradient increments must be small compared to unity.

The candidate time step size for a particular time step is the current best estimate of the time step size that will result in a maximum displacement gradient increment equal to a user-prescribed desired displacement gradient increment. The candidate is calculated as the previous time step size multiplied by the ratio of the desired displacement increment to the previous maximum displacement gradient increment.

If, for any time step, the maximum displacement gradient increment exceeds a user-prescribed maximum allowable displacement gradient increment, the time step will be repeated using a new (smaller) time step size which is the smallest of all the candidates.

CANDIDATE 3: This candidate is intended to control the magnitude of the maximum strain increment. The description is similar to that of CANDIDATE 2.

CANDIDATE 4: This candidate is intended to control the magnitude of the maximum plastic strain increment. The description is similar to that of CANDIDATE 2.

CANDIDATE 5: This candidate is equal to a user-prescribed maximum allowable time step size. This allows the user to place an upper bound on the time step sizes.

CANDIDATE 6: This candidate is equal to the previous time step size multiplied by a user-prescribed maximum allowable ratio of successive time step sizes.

CANDIDATE 7: This candidate is equal to the time step size required to reach the end of the current time interval. The time intervals are defined by the user. This candidate prevents the program from stepping over the boundaries between time intervals and insures that the endpoint of every time interval will coincide with the endpoint of a time step.

CANDIDATE 8: The intent of this candidate is to limit the magnitude of the plastic creep compliance matrix in comparison to the elastic compliance matrix. The plastic creep compliance matrix is a singular matrix which relates the stress increments to the plastic strain increments. The entries in this matrix increase in magnitude as the time step size increases. The elastic compliance matrix is a positive-definite matrix which relates the stress increments to the elastic strain increments. The sum of the elastic and plastic matrices forms the total compliance matrix which relates the stress increments to the elastic plus plastic strain increments. The total compliance matrix can be ill-conditioned (nearly singular) if the plastic part is large compared to the elastic part. This can lead to numerical difficulties in solving the finite element stiffness equations, so it is necessary to limit the time step size to avoid an ill-conditioned total compliance matrix at all integration points of the structure.

The elastic compliance is characterized by the reciprocal of the elastic modulus. The plastic creep compliance is characterized by the derivative of the generalized plastic strain increment with respect to the generalized stress. The compliance ratio is defined to be the ratio of plastic compliance to elastic compliance.

The candidate time step size for a particular time step is the current best estimate of the time step size that will result in equality between a user-prescribed ratio and the maximum compliance ratio.

CANDIDATE 9: This candidate is intended to limit the temperature increment that occurs during the time step. The candidate is calculated to be the largest time step size for which the maximum temperature increment does not exceed a user-prescribed allowable value.

It is necessary to limit the temperature increment for two reasons. First, in the material behavior model, a number of calculations, particularly those involving plastic strain increments, are performed assuming a constant temperature equal to the average temperature over the time step. This constant temperature approximation can result in insufficient accuracy if the temperature varies significantly during the time step. Second, if the thermal strain increments are sufficiently large, the structural stiffness matrix for the time increment will not be positive-definite, causing the program to have to repeat the time step using a smaller time step size.

****
2.3 GEOMETRY
****

****
2.3.1 INTRODUCTION
****

ACCEPT is presently programmed to handle only a structure which, in its initial or undeformed state, is in the form of a tube with a cross-section that is constant in the axial direction. The mid-surface, which is the surface lying midway between the inner and outer surfaces of the tube, can have a cross-section that is either an ellipse, an equilateral polygon, or an irregular polygon. Circumferential variations in wall thickness are allowed.

The finite element mesh can be set up to model either the entire circumference of the tube or just a part of the circumference. Whenever symmetry conditions permit modeling just a part of the circumference, it is advisable to do so since this reduces the size of the problem. The finite element mesh is automatically set up by the program from a small number of input parameters which characterize the mesh, as described in Sections 2.3.4 and 3.1.3.

****
2.3.2 COORDINATE SYSTEMS
****

Two coordinate systems are used to describe the geometry. One is a right-handed, orthogonal Cartesian coordinate system (X, Y, Z), as shown in Figure 2.2. The other is a cylindrical coordinate system (R, THETA, Z). The (X, Y) coordinates are related to the (R, THETA) coordinates by:

X = R*COS(THETA)

Y = R*SIN(THETA)

The units of X, Y, Z, and R are inches and the unit of THETA is degrees.

****
2.3.3 NODE AND ELEMENT NUMBERING
****

The nodes in a finite element mesh are numbered as follows: The nodes on the Z=0 plane are numbered first, followed by those on the next Z-plane, and so forth. On each Z-plane, the nodes on the THETA=0 line are numbered first, followed by those on the next THETA-line, and so forth. On each THETA-line, the node on the inside of the tube is numbered first, followed by the next node on the line, and so forth. This node numbering scheme is illustrated in Figure 2.2.

The elements are numbered in a similar fashion, as shown in Figure 2.2.

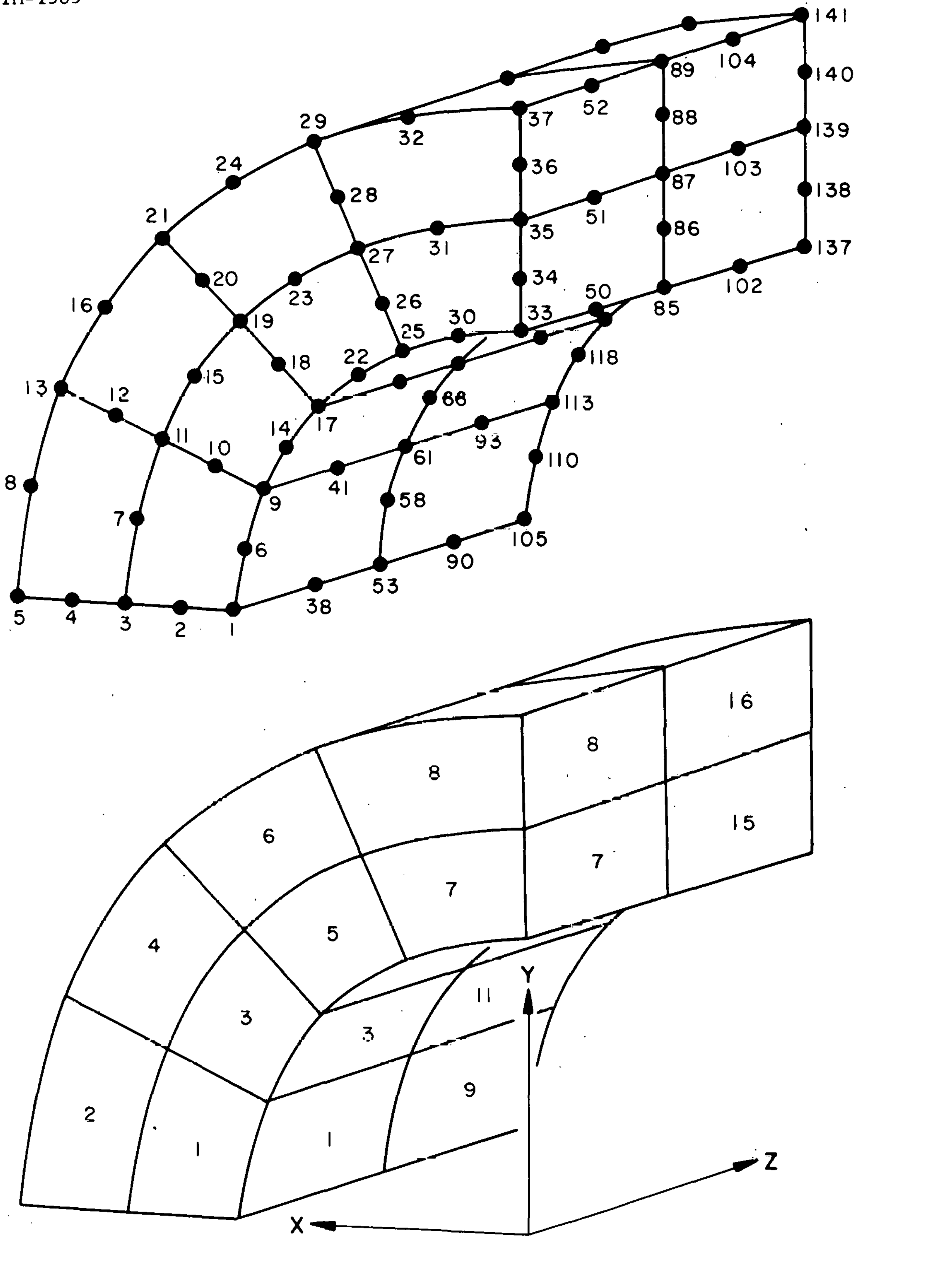


FIGURE 2.2 EXAMPLES OF FINITE ELEMENT MESHES FOR A 90° SECTION OF A TUBE, SHOWING NODE AND ELEMENT NUMBERS

****
2.3.4 ELLIPTICAL CROSS-SECTION
****

Figure 2.3 shows examples of cross-sections of tubes with elliptical mid-surfaces. See Appendix C for other types of cross-sections. The geometry of a cross-section is defined by the following parameters:

THETAM = maximum circumferential coordinate. (Equal to 180 degrees in Figure 2.3.)

THETAR = reference circumferential coordinate used to specify thickness variations. (Equal to 90 degrees in Figure 2.3a and 180 degrees in Figure 2.3b.)

R0 = radius from origin of coordinate system to outside of tube at THETA=0 degrees.

R90 = radius from origin of coordinate system to outside of tube at THETA = 90 degrees.

T0 = thickness of tube at THETA = 0 degrees.

TREF = thickness of tube at THETA = THETAR.

The thickness T, measured in the direction normal to the mid-surface, is given by

T = 0.5*(T0 + TREF) + 0.5*(T0 - TREF) *COS(180*THETA/THETAR)

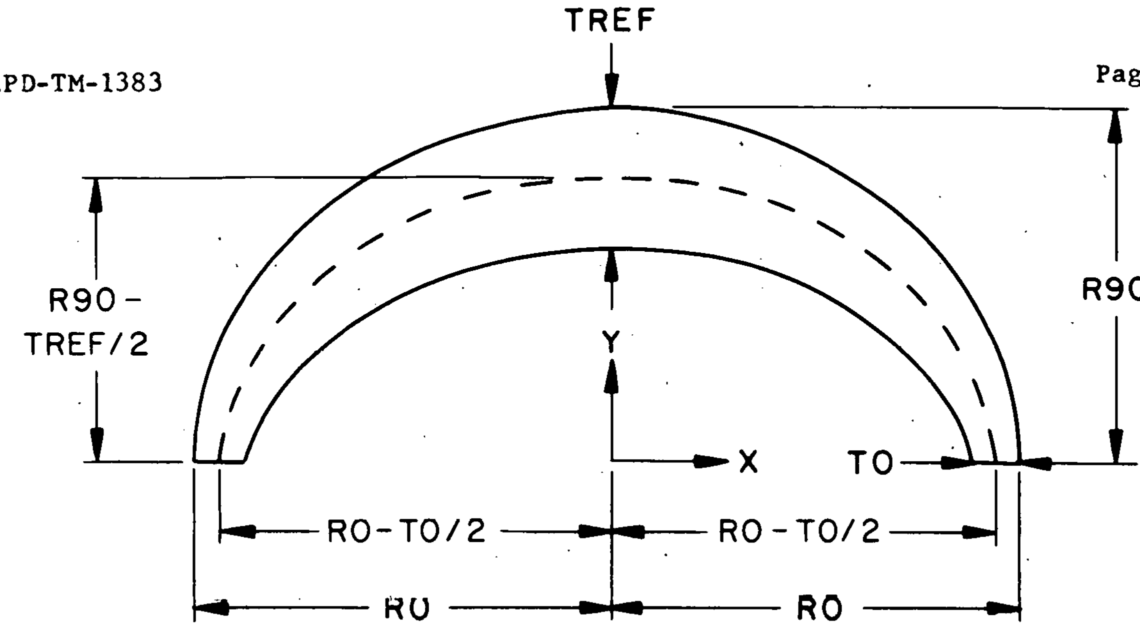
The elliptical mid-surface has principal diameters D0 and D90 given by

D0 = 2*R0 - T0

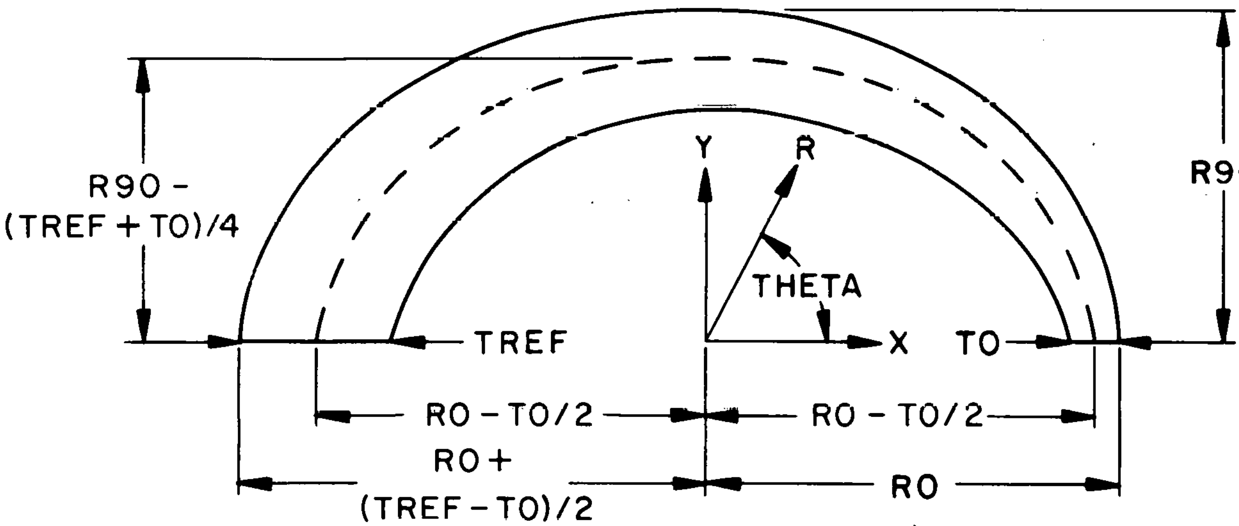
D90 = 2*R90 - T90

where T90 is the thickness at THETA = 90 degrees.

The finite element mesh is constructed such that the circumferential boundaries between elements are planes which intersect the mid-surface at right angles. The element spacing in the thickness direction is uniform while the element spacings in the circumferential and axial directions can be specified arbitrarily.



a. THETAM = 180°, THETAR = 90°



b. THETAM = 180°, THETAR = 180°

FIGURE 2.3 EXAMPLES OF 180° CROSS-SECTIONS OF TUBES WITH ELLIPTICAL MID-SURFACES

****
2.4 BOUNDARY, LOADING, AND ENVIRONMENTAL CONDITIONS
****

****
2.4.1 NODAL DISPLACEMENT AND FORCE BOUNDARY CONDITIONS
****

Certain default boundary conditions are built into the program to handle the most common types of problems. These default boundary conditions are:

(1.) The nodes on the Z=0 plane are fixed in the Z-direction.

(2.) The nodes on the Z=ZMAX plane are constrained to move as a plane in the Z-direction. The total axial force acting on this plane is prescribed as a piecewise linear function of time. This axial force is prescribed as the force that acts on a complete tube, whether or not the complete circumference is modelled. See Section 3.1.10.

(3.) If only a part of the circumference of the tube is modeled, the nodes on the two THETA = constant planes are fixed in the THETA-direction.

Any or all of the default boundary conditions can be overridden. Also, any node can be fixed in the R, THETA, or Z-directions. See also Section 3.1.11.

****
2.4.2 PRESSURE LOADS
****

Any number of pressure loads can be prescribed as piecewise linear functions of time. Any such pressure load can be applied to one or more element surfaces which are on the inside or outside of the tube. The program accounts for finite changes in geometry, so these loads are interpreted as true pressure loads; i.e., force per unit of actual area, always acting normal to the surface. See also Section 3.1.9.

****
2.4.3 TEMPERATURE
****

ACCEPT is primarily intended for problems where the temperature is essentially uniform over the entire model. The program is, therefore, not automatically linked with a heat conduction program. The temperature is assumed to be uniform within any given element, but may be different for different elements.

Any number of temperature histories can be prescribed as piecewise linear functions of time. Any such history can be applied to one or more elements. See also Section 3.1.7.

****
2.4.4 INTERACTION WITH RIGID SURFACES
****

ACCEPT has a capability which allows frictionless contact-separation interaction of the inner or outer wall of the tube with one or more rigid surfaces. This capability is intended to allow modeling of interaction of reactor fuel rod cladding with fuel pellets or external supports.

Each rigid surface is a circular cylinder centered on the Z-axis. The Z-coordinate of each end and the radius of a surface can change as prescribed piecewise linear functions of time.

See also Section 3.1.12.

****
3. PROGRAM OPERATION
****

The following describes the methods that must be used to access and use the ACCEPT program at Bettis using standard programming procedures described in Reference 5.

The first part describes the input for ACCEPT, and this is correlated to previous descriptions of program capabilities.

The second part describes the limitations of the program in terms of the size of problems that may be run. In terms of speed, the procedure for solution of the sets of linear equations that are generated at each time-step is approximately 5 times faster than the procedure used in the MATUS program (Reference 2).

The third part describes the methods used to save and retrieve data generated by ACCEPT. The files generated by ACCEPT may be read by ACCEPT or by ACCUSE (Section 4) or by EDFILE (Appendix A). Files generated by ACCEPT are organized such that all data of every type may be stored on one file. In the most general case, ACCEPT, ACCUSE, or EDFILE will then automatically select and access the appropriate data needed at any particular point in a computer run.

The method of obtaining ACCEPT, ACCUSE, and EDFILE for execution on a Bettis computer is by putting any or all of the following in the control card stream, depending on which programs are desired.

```
PROGM(ACCEPT)
PROGM(ACCUSE)
PROGM(EDFILE)
```

Actual execution of the programs then takes place when any or all of the following cards are placed in the control card stream.

```
ACCEPT.
ACCUSE.
EDFILE.
```

Some of the terms which will be used in subsequent sections are as follows. SCM is the Small Core Memory of the computer. LCM is the Large Core Memory of the computer. FTB is the name of the scratch I/O package of subroutines used in ACCEPT, and it is described in Reference 5. AFM is the Advanced File Manager. It is the set of subroutines which handle permanent storage and retrieval of the data produced by ACCEPT. This is also described in Reference 5.

****
3.1 INPUT DESCRIPTION
****

This section describes the input to the ACCEPT program.

Section 3.1.1 gives a few rules concerning the Bettis Input Package (Reference 5), which is used to read and process all ACCEPT input data.

In each succeeding section, a group of cards is described. In each case, the cards have similar identification numbers and are used to input related data. Within the section, each card is described along with cross-references to descriptions of the related program capabilities.

Section 3.1.13 describes "condensed format" integer input, which is a method of inputting a large amount of integer data in an abbreviated manner.

****
3.1.1 THE BETTIS INPUT PACKAGE
****

The following are a few rules concerning the format of the input for the ACCEPT and ACCUSE programs.

(1.) Free-field input is allowed, where data items are separated by commas.

(2.) Each card begins with an identification number. Therefore, the cards may be input in any order.

(3.) More than one card with the same id number may be input. The last such card is the one that is effective.

(4.) The input is printed on each run.

(5.) Any data field may be repeated as follows,
, /integer repeat count/ field,

(6.) Any card may be continued by using a + as the first non-blank character of a continuation card.

(7.) A title card is allowed, which is printed at the top of each page. This is identified by = as the first non-blank character.

(8.) Any number of comment cards are allowed in the input. These are identified by * as the first non-blank character.

(9.) Comments may be added to any input card after a $ on the card.

****
3.1.2 RESTARTING
****

1000, NOSTEP, NOSECT (OPTIONAL)

This card is used to invoke the ACCEPT restart option. This option allows the user to restart a problem after any time-step for which the results have been calculated and stored. Before reading this Section, the user should acquire a thorough knowledge of Section 3.3 on FILING.

NOSTEP = access number of data to be used to restart the problem. This number is incremented and printed at the end of time-steps when data is stored. This number is also printed as part of the final summary edit of ovalities and diameters.

NOSECT = number of the sections of type TSTEPS and BCONDS (Section 3.3.4) to be used in the restart problem. For instance, NOSECT = 3 means that sections TSTEPS03 and BCONDS03 will be used. If this variable is set to 0 or omitted, the last sections of these types written to the file will be used. If sections other than those last written to the file are to be used, then NOSECT can be determined from the printout for the run in which the data was stored. NOSECT is always found in the last two characters of the section name.

There are at least two major cases where restarts will be used. The steps to be taken in these cases are given below.

CASE 1 A problem has previously encountered a time limit. All that is desired is to pick up where the previous problem left off.

(1.) Add the control card:

FETCH(I= "name" ,V=i,T=303,D=4)

to obtain the file of results stored at the end of the previous run. An example of this card is:

FETCH(I=TUBE 1,V=3,T=303,D=4)

(2.) Change the STORE card to read:

STORE(I= "name" ,V=(i+1)-(i+10),T=303)

An example of this card is:

STORE(I=TUBE 1,V=4-13,T=303)

(3.) Determine NOSTEP and add the input card:

1000,NOSTEP,NOSECT

to the input deck.

(4.) (Refer to card 21ccc.) Unless otherwise specified, the initial time-step in the restart problem will be taken to be:

0.001 * (time at end of current interval - restart time)

This may be overridden by specifying the second parameter on the 21ccc card for the time-interval in which the problem is restarted. A problem is defined to be restarted in the first time-interval whose end-time is greater than the restart-time.

The 21ccc cards may be left as they were in the original run. If zeroes are used on any such card, ACCEPT will pick up the proper parameter values from earlier cards.

(5.) A file which results from a restart problem will contain all data that was on the input file, plus all data generated in the current job. This means that files may grow to be quite large, particularly if a sequence of restart problems is to be run. This can cause difficulties, primarily in storing and retrieving files from tape.

The EDFILE program (Appendix A) may be used to limit the size of a file.

CASE 2. It is desired to restart a problem at several points in time. One example of this is a problem in which it is desired to simulate unloading at several points in time.

(1.) This is the same as (1.) for CASE 1.

(2.) Change the STORE card to read:

STORE(I= "new name" ,V=1-10,T=303)

where "new name" is a different I parameter than is on the FETCH card. An example of this card is:

STORE(I=TUBE 1-TEST STUDY 1,V=1-10,T=303)

(3.) This is the same as (3.) for CASE 1.

(4.) This is the same as (4.) for CASE 1.

(5.) The use of EDFILE to purge data from files is not generally recommended in this case. The reason for this is that it is less likely that a restart will be done more than once or twice for any particular case. Thus, files will not grow as large as they would in CASE 1. Also, it is important to retain related data on the same file for later use in ACCUSE. It is also important to use the file output from the original run as input for each case.

(6.) This is the same as (6.) for CASE 1.

****
3.1.3 GEOMETRY DATA
****

The purpose of the following input cards is to allow the description of the geometry of a tube to ACCEPT. See also Section 2.3 and Appendix C.

10000, INDGEM, NTHICK, NCIRCM, NAXIAL (REQUIRED)

(1.) INDGEM = geometry option indicator (integer).
(Set = 1 for elliptical cross-section.
For other options, see Appendix C.)

(2.) NTHICK = number of elements through the thickness (integer).

(3.) NCIRCM = number of elements around the circumference of the tube.
(integer)

(4.) NAXIAL = number of elements along the axis of the tube.
(integer)

11000, ZMAX, THETAM, THETAR, R0, R90, T0, TREF (REQUIRED)

(1.) ZMAX = maximum axial coordinate (real).
= length of tube in inches.

(2.) THETAM = maximum circumferential coordinate in degrees (real).

(3.) THETAR = reference circumferential coordinate (degrees) used to specify thickness variations (real). (See below.)

(4.) R0 = outside radius of tube at THETA = 0. (real).
= inches.

(5.) R90 = outside radius of tube at THETA = 90. (real).
= inches.

(6.) T0 = thickness of tube at THETA = 0 (real).
= inches.

(7.) TREF = thickness of tube at THETA = THETAR (real).
= inches.

The thickness variations in a cross-section of a tube are determined by a cosine wave, as described in Section 2.3.4. The maximum and minimum thicknesses occur at THETA = 0. and THETA = THETAR, respectively, or vice versa. The period of the cosine wave is 2 * THETAR.

11001, N1, Z1, N2, Z2, ..., NLAST, ZLAST (REQUIRED)

(1.) Ni = axial element layer number (integer).

(2.) Zi = axial coordinate at end of layer Ni (real).

Ni and Zi must be input such that,

1 ≤ N1 < N2 < ... < NLAST = NAXIAL, and

0 < Z1 < Z2 < ... < ZLAST = ZMAX.

Examples,

(A.) The card 11001, 5, 10. will generate a mesh with element boundaries at Z = 0., 2., 4., 6., 8., 10.

(B.) The card 11001, 2, 2., 5, 14. will generate a mesh with the element boundaries at Z = 0., 1., 2., 6., 10., 14.

11002, N1, THETA1, N2, THETA2, ..., NLAST, THETALAST (REQUIRED)

(1.) Ni = circumferential element layer numer (integer).

(2.) THETAi = circumferential coordinate at end of layer i (real) in degrees.

These pairs are input in a manner similar to those on card 11001.

****
3.1.4 TIME INTERVAL DATA
****

20000, TSTART (REQUIRED)

TSTART = time at start of problem in hours (real).
This is ignored in restart problems.

21ccc, TENDI, SIZINI, PARAM(1), ..., PARAM(12) (REQUIRED)

where ccc = 001 to nnn, nnn ≤ 999, and nnn = number of time intervals in the problem. There must be one such card for every time interval, and the cards must be numbered consecutively from 21001 to 21nnn.

(1.) TENDI = time at the end of the interval in hours (real).

(2.) SIZINI = initial time-step size for the interval (real).
This must be input for the first interval. If set equal to 0.0 for subsequent intervals, this will be calculated by the program.

(3.) PARAM = vector of 12 user-specified parameters for the interval used in controlling the time-step size (real). If any entry is set to 0.0, the value for the previous interval is used. See also Section 2.2.5.

entry 1 = maximum allowable stress error in psi.
entry 2 = maximum allowable displacement gradient increment.
entry 3 = maximum allowable strain increment.
entry 4 = maximum allowable plastic strain increment.

entry 5 = desired stress error in psi.
entry 6 = desired displacement gradient increment.
entry 7 = desired strain increment.
entry 8 = desired plastic strain increment.

entry 9 = maximum allowable time-step size in hours.
entry 10 = maximum allowable ratio of next time-step size to previous time-step size.
entry 11 = maximum allowable ratio of derivative of plastic strain rate with respect to generalized stress to derivative of elastic strain rate with respect to generalized stress.
entry 12 = maximum allowed temperature increment in a time-step in degrees F. (default = 100 degrees if this parameter is not supplied).

It is required that,

$$2 * PARAM(i + 4) \le PARAM(i)$$

where i = 1, 2, 3, 4.

Recommended Values:

PARAM(1) = 0.01 to 0.05 times estimated maximum stress.
PARAM(2) = 0.005 to 0.05.
PARAM(3) = 0.005 to 0.05.
PARAM(4) = 0.005 to 0.05.
PARAM(5) = 0.2 * PARAM(1).
PARAM(6) = 0.2 * PARAM(2).
PARAM(7) = 0.2 * PARAM(3).
PARAM(8) = 0.2 * PARAM(4).
PARAM(10) = 2 to 10.
PARAM(11) = 10 to 20.

22ccc, TIMLIM, OVALIM (OPTIONAL)

where ccc = 001 to nnn, nnn ≤ 999, and nnn = number of time-intervals in the problem.

(1.) TIMLIM = lower limit of size of time-steps (hours) in this interval (real).
(2.) OVALIM = upper limit of ovality (inches) that may occur in this interval (real). This is compared to the difference between the maximum and minimum outer diameters at Z = 0.0 at each time-step.

The parameters on this card will apply to time-interval ccc. This card is OPTIONAL. Only the card for a time-interval for which the time-step size or the ovality is to be limited need be input into the program.

If either limit is set to 0.0, the corresponding variable will be taken to be essentially unlimited. If this card is not supplied for an interval, both of the corresponding variables for that interval will be taken to be essentially unlimited.

If either limit is reached, ACCEPT will,
(1.) print and store the results for the last step, and
(2.) terminate.

22000, TIMALL, OVALAL (OPTIONAL)

(1.) TIMALL = lower limit of size of time-steps (hours) in the overall problem (real).
(2.) OVALAL = upper limit of ovality (inches) that may occur in the overall problem (real). This is compared to the difference between the maximum and minimum outer diameters at each time-step.

The parameters on this card will apply to any time-interval for which a card 22ccc has not been supplied. If a card 22ccc is supplied for any interval ccc, then the parameters on card 22ccc will override those on card 22000, but only for interval ccc. If neither card is supplied, then TIMALL and OVALAL will be set such that both quantities are essentially unlimited in the program.

If either limit is reached, ACCEPT will,
(1.) print and store the results for the last step, and
(2.) terminate.

The program will automatically restart any time-step in which any of a number of conditions, such as excessively high strain increments, is encountered during the step.

If such a condition is encountered, the program will halve the time-step size and try the step again. It will do this up to a maximum of 5 times for any step. If the limit is reached, the program will store the last good results and exit gracefully.

The limit of 5 retries may be altered by using the following input card:

20001, MAXRES (OPTIONAL)

If this card is used, then MAXRES (integer) becomes the new upper limit on the number of internal restarts that will be attempted by the program.

The limitation on the number of internal restarts may be associated with the size of the step by the use of card 20001 and either card 22000 or card 22ccc. By setting MAXRES to a large integer and defining a lower limit on the size of steps on either card 22000 or card 22ccc, the program will try to restart until the time-step size reaches the limit imposed on card 22000 or card 22ccc.

****
3.1.5 STORAGE CONTROL
****

Data is normally written by ACCEPT to the type 303 output file at the end of each user-specified time-interval and at the end of a computer run. An exception to this is, if one of the first four entries in the PARAM array on card 21ccc (Section 3.1.4) is exceeded during a time step, then data is not stored at the end of the time step. Optional input cards provide a number of user controls over this process, such that additional data may be stored when desired.

In what follows, the word "store" is used to refer to the process of writing data onto the output file. Actual storage of the file on a hardware device, however, does not take place until the AFM (Reference 5) wrap-up at the end of a computer run.

23000, ISTORE, OSTORE, TSTORE (OPTIONAL)

This card is used to govern storage throughout a computer run. The parameters on this card can be used to cause ACCEPT to store data at steps other than where data would normally be stored.

ISTORE = parameter which controls storage according to the number of the time-step (integer).

> 0 implies data will be stored at the end of steps 1, 1+ISTORE, 1+2*ISTORE, and so forth.
= 0 implies this parameter does not apply (default).
= - 1 implies all storage is suppressed, except at the end of a computer run. This takes precedence over all other storage options.

OSTORE = parameter which controls storage according to the outer-surface ovality (real). This ovality is defined as the difference between the maximum and minimum diameters at Z = 0.0 at the end of a time-step. If the outer-surface ovality exceeds OSTORE, data is stored at the end of the step. The default is 1.E100. If this is input as 0.0, ACCEPT will set OSTORE to 1.E100.

TSTORE = parameter which governs storage according to the size of the time-step just completed (real). If the time-step is less than TSTORE in length, data is stored at the end of the time-step. The default is 0.0

23ccc, ISTORE, OSTORE, TSTORE (OPTIONAL)

where ccc = 001 to nnn, nnn ≤ 999, and nnn = number of time-intervals in the problem.

The parameters on this card have the same meaning as those on card 23000, except that these parameters apply strictly to time-interval ccc. Also, ISTORE = - 1 has no meaning here, since this is the same as the default case.

The global values of ISTORE, OSTORE, and TSTORE are defined as the default values 0, 1.E100, and 0.0, respectively. If card 23000 is input, the global values are reset to the entries on card 23000. The global values of ISTORE, OSTORE, and TSTORE apply to time-interval ccc, unless card 23ccc is input. For instance, if card 23003 is input, the values of ISTORE, OSTORE, and TSTORE are those on 23003 in interval 3, and they are 0, 1.E100, and 0.0, respectively, in intervals 2 and 4, unless card 23002 or 23004 is input.

24001, TIME1, TIME2, ... (OPTIONAL)

If this card is input, data is stored at the end of the first time-step whose ending time exceeds TIMEi, for each entry TIMEi. For instance, if

24001, 1.5, 25.0

is input, data is stored at the end of the first time-step whose ending time exceeds 1.5 hours, and at the end of the first step whose end exceeds 25.0 hours.

Entries on this card do not have to be in increasing sequence.

****
3.1.6 MATERIAL PROPERTY DATA
****

30000, MTABL1, MTABL2, ... (REQUIRED)

MTABLi = indicator of type of properties that will be used in material property table i (integer), i = 1 to 9.

where

MTABLi = 1 means that material properties for 70 per-cent cold-worked stress relief annealed Zircaloy will be used.

MTABLi = 2 means that material properties for recrystalization annealed Zircaloy will be used.

The above card is a method of selecting a set of material properties from tables kept internally in ACCEPT. The values in the tables may be modified by using the optional cards 30jcc, where j = i - 1 = 0 to 8. The tables may be assigned to specific elements by using the optional card 33001, where i = 1 to 9 = number of a material property table.

30jcc, ENTRY1, ENTRY2, ..., ENTRYLAST (OPTIONAL)

where j = 0 to 8, cc = 01 to 16.

ENTRYi = an entry in material property table j+1.

These optional cards may be used to change parts of the material property table. Each card corresponds to a keyword in the table and contains a list of words as follows. (See Appendix B for a description of these variables.)

CARD	KEYWORD	CONTENTS
30j01	TMP1UN	priml(1), ..., priml(15)
30j03	TMP2UN	prim3(1), ..., prim3(15)
30j05	TMP3UN	prim5(1), ..., prim5(15)
30j07	RPTEN	rth, rz1, rz2, pth, pz1, pz2
30j08	RPCOM	rcth, rcz1, rcz2, pcth, pcz1, pcz2
30j09	YRATIO	yratio, yratz1, yratz2
30j10	BDFL	bz1, etrnsc, dfz1, pfact, qfaz1, efz2, bcez1, bnz2, egmin
30j12	TEXTR	f(1), f(2), f(3)
30j14	ENU	cmod, ctmod, cnu, ctnu
30j15	CZERO	czero(1,1), czero(1,2), ..., czero(1,6), czero(2,1), ..., czero(6,6)
30j16	CCOEF	ccoef(1,1), ccoef(1,2), ..., ccoef(1,6), ccoef(2,1), ..., ccoef(6,6)

Inclusion of any of the above cards will result in the replacement of the table entries which immediately follow the keyword. Replacement begins with the first table entry following the keyword. The number of entries replaced is the same as the number of entries on the card.

The variables rz1, rz2, pz1, pz2, rcz1, rcz2, pcz1, pcz2, yratz1, yratz2, bz1, dfz1, qfaz1, bcez1, and bnz2 are not used in the current version of ACCEPT.

31000, RZZZZI, EHEI, RZZZZ, EZZ(1), EZZ(2), EZZ(3), FZZZZZ (OPTIONAL)

EHEI = initial value of strain hardening strain (real).

EHEI defaults to 1.E-6 if this card is not provided. EHEI must be at least as great as EGMIN, the minimum allowed value of the thermal strain rate. The latter is the last entry in the BDFL portion of the material property table (card 30j10). If it is not, EHEI will be reset to EGMIN, and warning messages will be printed.

The variables RZZZZI, RZZZZ, EZZ, and FZZZZ are not used in the current version of ACCEPT.

32000, IXTHST, IXZZST, IXPLST, TEMLIM (OPTIONAL)

The parameters on this card are indicators which allow the user to turn off the calculation of selected strains. "Turning off" the corresponding strain means setting it to zero.

(1.) IXTHST = turn off the calculation of thermal strains if this indicator is set to 1.
(2.) IXPLST = turn off the calculation of plastic strains if this indicator is set to 1.
(3.) TEMLIM = temperature below which plastic strain increments are set to 0. That is, only elastic behavior occurs below this temperature. The current default value is 300.0 degrees. This is an optional parameter which may or may not be added to this card.

The variable IXZZST is not used in the current version of ACCEPT.

3300i, NELEM1, NELEM2, ..., NELEMLAST (OPTIONAL)

where i = 1 to 9 = number of a material property table.

NELEMi = number of an element to which material property table i is assigned (integer).

The entries on this card may be written in "condensed format", as described in Section 3.1.13. If this card is omitted, material property table 1 is assigned to all elements. If an element is assigned more than one material property table, the last such assignment is the one that will apply.

35ccc, ath,az1,az2, bth,bz1,bz2, cth,cz1,cz2 (OPTIONAL)

where ccc = 001 to nnn, nnn≤999, and nnn = number of material property tables in the problem.

The entries on this card (real) permit user control over the dependence of anisotropic creep on the state of shear stress. The entries are the shear stress coefficients used to define the generalized stresses for thermal (th) creep. See Appendix B.

This card is optional. If it is not input, the values are set according to the following equations:

```
ath = ( 1 / yratio )**2 * ( 6 * rcth ) / ( rcth + 1 )

bth = ( 1 / yratio )**2 * 6 / ( rcth + 1 )

cth = ( 1 / yratio )**2 * ( 6 * rcth ) / ( pcth * ( rcth + 1 ) )
```

See Appendix B for the definitions of the variables used in these equations.

The variables az1, az2, bz1, bz2, cz1, and cz2 are not used in the current version of ACCEPT.

****
3.1.7 TEMPERATURE DATA
****

40ccc, TIME1, TEMP1, TIME2, TEMP2, ..., TIMELAST, TEMPLAST (REQUIRED)

where ccc = 001 to nnn, nnn ≤ 999, and nnn = number of temperature history tables in the problem. There must be one such card for every temperature history table in the problem, and the cards must be numbered consecutively from 40001 to 40nnn. See also Section 2.4.3.

(1.) TIMEi = time (in hours) at which an element is at the corresponding temperature (real).

(2.) TEMPi = temperature (in degrees Fahrenheit) corresponding to TIMEi (real).

where i = 1 to LAST.

The temperatures are obtained by linear interpolation using these tables. If the current time ≤ TIME1, the current temperature is TEMP1. If TIMELAST ≤ the current time, the current temperature is TEMPLAST. The table entries must be arranged such that,

TIME1 < TIME2 < ... .

For a time step, the assumed temperature in the material property representation is the average of the interpolated temperature at the beginning of the time step and the interpolated temperature at the end of the time step.

41ccc, IELEM1, IELEM2, ..., IELEMLAST (REQUIRED)

where ccc = 001 to nnn, nnn ≤ 999, and nnn = number of temperature history tables in the problem. There must be one such card for every temperature history table in the problem, and the cards must be numbered consecutively from 41001 to 41nnn. If an element is assigned more than one temperature history table, the last such assignment is the one that will apply.

IELEMi = number of an element to which temperature history table ccc is assigned.

This card may be written in "condensed format", as described in Section 3.1.13.

****
3.1.9 PRESSURE LOAD DATA
****

60ccc, TIME1, PRESS1, TIME2, PRESS2, ..., TIMELAST, PRESSLAST (REQUIRED)

61ccc, IELEM1, IELEM2, ..., IELEMLAST (REQUIRED)

62ccc, IELEM1, IELEM2, ..., IELEMLAST (REQUIRED)

These cards are the same as 40ccc and 41ccc, except that they describe the pressure load history tables. The units for pressures are pounds per square inch. The last two cards list the elements to which the corresponding pressure load table applies on the inside of the tube (61ccc) and on the outside of the tube (62ccc).

See also Section 2.4.2.

****
3.1.10 AXIAL LOAD DATA
****

70000, TIME1, LOAD1, TIME2, LOAD2, ..., TIMELAST, LOADLAST (REQUIRED)

This card describes the axial load history table. The units for axial loads are pounds. At any point in the problem, the axial load is obtained by linear interpolation from this table. If time ≤ TIME1, load = LOAD1. If TIMELAST ≤ time, load = LOADLAST.

The load values should be input to correspond to the axial load acting on a complete 360-degree tube, whether or not the complete circumference is modelled in the problem. The loads obtained from the table will be multiplied by 360./THETAM before being applied to the finite element model.

See also Section 2.4.1.

****
3.1.11 FIXED DISPLACEMENT DATA
****

8000c, NODE1, NODE2, ..., NODELAST (NORMALLY OPTIONAL. REQUIRED IF THETAM = 180. OR 360.)

NODEi = node whose displacement is fixed in direction c = 1, 2, 3 (integer). The directions in this case correspond to R, THETA, and Z. See also Section 2.4.1.

The list of nodes may be written in "condensed format", as defined in Section 3.1.13.

The axial displacement on the Z = 0.0 plane is normally fixed (0.0). The displacements normal to the THETA = 0.0 and THETA = THETAM planes will also normally be fixed (0.0).

Except for two cases, rigid body motions are eliminated by the default boundary conditions. These two cases are given below, along with one suggested solution for this problem. If THETAM = 180., one solution is to fix the displacement of at least one node on the Y-axis in the THETA-direction. If THETAM = 360., the same is true, but also the displacements of at least two nodes on the X-axis should be fixed in the THETA-direction. In the last case, the two nodes on the X-axis should be 180 degrees apart.

80010, INDZ0, INDZMX, INDT0, INDTMX (OPTIONAL)

The normal state of the structure (see Section 2.4.1) in ACCEPT is that,

(a.) the nodes on the Z = 0.0 plane are constrained such that they do not move in the Z-direction,
(b.) the nodes on the Z = ZMAX plane are required to displace together as a plane in the Z-direction, and,

except for a 360-degree tube,

(c.) the nodes on the THETA = 0.0 plane are constrained such that they do not move in the circumferential direction, and
(d.) the nodes on the THETA = THETAMAX plane are constrained such that they do not move in the circumferential direction.

This card may be used to relax any or all of these conditions.

INDZ0 = indicator if the condition on the Z = 0.0 plane is to be relaxed.
0 = no (default).
1 = yes.
INDZMX = indicator if the condition on the Z = ZMAX plane is to be relaxed.
0 = no (default).
1 = yes.
INDT0 = indicator if the condition on the THETA = 0 plane is to be relaxed.
0 = no (default).
1 = yes.
INDTMX = indicator if the condition on the THETA = THETAMAX plane is to be relaxed.
0 = no (default).
1 = yes.

The axial loads specified on card 70000 will be ignored if the condition on the Z = ZMAX plane is relaxed (INDZMX = 1).

****
3.1.12 CONTACT DATA
****

```
900ss, TIME1, ZLOW1,   TIME2, ZLOW2,   ..., TIMELAST, ZLOWLAST    (OPTIONAL)
901ss, TIME1, ZHIGH1,  TIME2, ZHIGH2,  ..., TIMELAST, ZHIGHLAST   (OPTIONAL)
902ss, TIME1, RADIUS1, TIME2, RADIUS2, ..., TIMELAST, RADIUSLAST  (OPTIONAL)
903ss, ELINE1, ELINE2, ..., ELINELAST  (OPTIONAL)
904ss, NLINE1, NLINE2, ..., NLINELAST  (OPTIONAL)
905ss, NAXIAL1, NAXIAL2, ..., NAXIALLAST  (OPTIONAL)
```

where ss = 01 to ns, ns ≤ 99, and ns = number of contact surfaces that may interact with the tube. See also Section 2.4.4.

The parameters on the above cards are:

(1.) ZLOWi = lower bound of contact surface ss at TIMEi. (real)
(2.) ZHIGHi = upper bound of contact surface ss at TIMEi. (real)
(3.) RADIUSi = radius of contact surface ss at TIMEi. (real)
(4.) ELINEi = number of a line of elements around the circumference all of which may potentially interact with contact surface ss. (integer)
(5.) NLINEi = number of a line of nodes around the circumference all of which may potentially interact with contact surface ss. (integer)
(6.) NAXIALi = number of a line of nodes down the Z-axis that lies within the contact area for surface ss (integer).

The first 3 cards express the location of contact surface ss as a piecewise linear function of time. Each contact surface is assumed to have a cylindrical shape. The entries on the first 3 cards have units in hours (time) and inches (length). These 3 cards are OPTIONAL. However, if one card is supplied for contact surface ss, then all 3 cards must be supplied. In addition, either card 903ss or card 904ss (but not both) must be supplied.

The fourth, fifth, and sixth cards define which nodes of the mesh may possibly touch contact surface ss.

Each entry on card 903ss is the number of a line of elements around the circumference of the tube. The line of elements around the circumference at Z = 0.0 is given the number 1. The next line of elements around the circumference as one moves down the Z-axis in the positive direction is line number 2, and so forth. Any element on any line of elements designated by this card may potentially come into contact with contact surface ss. Thus, all nodes on the inside of any line of elements designated by this card will be designated as potential contact nodes, except as modified by card 905ss.

Each entry on card 904ss is the number of a line of nodes around the circumference of the tube. The line of nodes around the circumference at Z = 0.0 is given the number 1. The next line of nodes around the circumference as one moves down the Z-axis in the positive direction is line number 2, and so forth. Any node on any line of nodes designated by this card may potentially come into contact with contact surface ss, except as modified by card 905ss.

Each entry on card 905ss is the number of a line of nodes down the Z-axis of the tube. The line of nodes down the Z-axis at THETA = 0.0 is given the number 1. As THETA increases, the next line of nodes is give the number 2, and so forth. It is normally assumed that a surface can potentially come into contact with all nodes around the circumference at a given axial location. Card 905ss may be used to relax this condition and restrict possible contact to a subset of the nodes at a given axial location. This permits the solution of contact problems in which a contact surface extends over only a part of the circumference.

Entries on cards 903ss, 904ss, and 905ss may be written in "condensed format", as described in Section 3.1.13.

A consideration in setting up contact problems is as follows. There are three nodes on each edge of an element, two on the ends and one in the middle. If the one in the middle of any edge is designated as a possible contact node, then all nodes on that edge must be designated as possible contact nodes.

The program permits the specification of a contact surface with a time-varying elliptical cross-section. The major axis of the ellipse may be specified to lie on either the x-axis (THETA = 0.0) or the y-axis (THETA = 90.0).

Figure 3.1 shows the case in which the major axis of the ellipse lies on the x-axis.

The program permits the input of an ovality and average radius, where it is assumed that:

$$\text{(ovality)} \quad W = 2 * (R(x) - R(y)) \qquad (1)$$

$$\text{(average radius)} \quad R = (R(x) + R(y))/2 \qquad (2)$$

and R(x), R(y) = radii of major, minor axes, respectively. From the above definitions, it follows that:

$$R(x) = R + W/4 \qquad (3)$$

$$R(y) = R - W/4 \qquad (4)$$

The input required for the elliptical option consists of the following cards:

902SS, TIME1, RADIUS1, TIME2, RADIUS2, ..., TIMELAST, RADIUSLAST (REQUIRED)

906SS, TIME1, OMEGA1, TIME2, OMEGA2, ..., TIMELAST, OMEGALAST (OPTIONAL)

The entries on card 902ss then comprise a table of average radii for contact surface ss. The entries on card 906ss comprise a table of ovalities for contact surface ss.

Card 902ss is always required whenever the ACCEPT contact option is invoked. Card 906ss may then also be supplied, but it is optional. If 906ss is not supplied, then contact surface ss will be assumed to be circular in shape. The same is true whenever the ovality is input as 0.0. The input of a negative ovality will cause the major axis of the ellipse to lie on the y-axis.

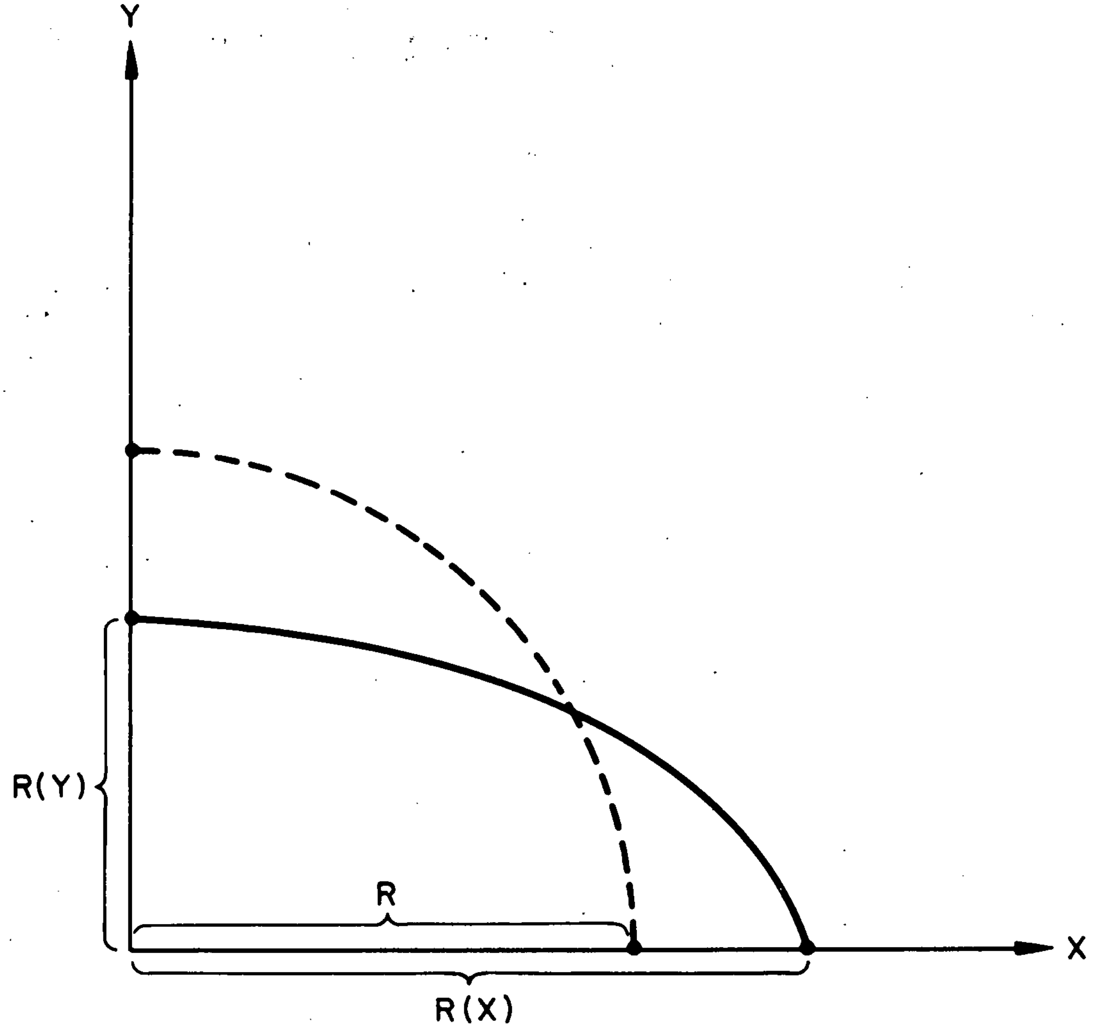


FIGURE 3.1 QUARTER OF ELLIPTICAL CROSS SECTION

91001, INDOUT (OPTIONAL)

This card may be used to change the definition of a contact problem to one in which contact will occur with the nodes on the outside surface.

INDOUT = indicator whether this is an inside or an outside contact problem (integer).

0 = an inside contact problem (default).
1 = an outside contact problem.

If INDOUT = 1, all definitions of the parameters on cards 900ss through 905ss now apply to a contact surface impinging on a tube from the outside.

****
3.1.13 CONDENSED FORMAT INPUT
****

Various cards used to input integer data may be written in "condensed format". In this format, the integers are input in "sets". Each set may take the form:

n1,-n2,-n3

The meaning of the above is: "input all integers from n1 to n2, but not necessarily including n2, in increments of n3". For instance, the set:

4,-17,-3

will be taken as a shorthand way of inputting the integers 4, 7, 10, 13, and 16.

The entries -n2 and -n3 are optional in each set. If -n3 is omitted, the increment is taken as one. If -n2 is omitted, the input set includes exactly one integer.

Sets do not have to be input in the order of increasing magnitude. Any number of sets can be input on a card.

****
3.2 SIZE LIMITATIONS
****

The following limitations apply to the size of the problems that can be run on the ACCEPT program. The number of nodes is essentially unlimited. The number of elements is limited to 8176, based on the availability of a disk that has a useable space of 30 million 60-bit words. Most practical problems will be run with far fewer elements. The maximum wavefront is limited to 789 if a Large Core Memory (LCM) is available with at least 262,144 60-bit words. The maximum wavefront is limited to 1100 if an additional 65,536 60-bit words are available in LCM.

The above limitations apply to a CDC-7600. In the CDC-6600 version of ACCEPT, all FTB files that are on disk in the CDC-7600 version are placed in LCM. In this case, problems should not be run with more than 30 elements, and no contact problems should be run.

****
3.3 FILING
****

ACCEPT, ACCUSE, and related programs write and read a single, sectioned, interface format file (Reference 5). Within this file, all the different kinds of data are written as individual sections of the file. Thus, one section will contain the boundary conditions, another will contain the time-step data, and so forth. In this way, all the data for a single problem can be contained in a single file.

In addition, new data can be added to the file on succeeding runs, and more than one section of the same kind of data can exist in the file. Each such section will be tagged with a distinct name. This means, for example, that problems can be run with different sets of boundary conditions, and all results can be contained in the same file.

Finally, any combination of programs can be run, and all required input data can be supplied by fetching one file.

****
3.3.1 THE STORE CARD
****

The following Advanced File Manager (AFM) card is required to run any program in which data is written:

STORE(I=______, V=1-10, T=303)

The I parameter is a user-selected file identification of up to 20 characters. The T parameter specifies that the data type of the output file will be 303.

The "V=1-10" parameter specifies that the version number of the output file will be in the range 1 to 10. There will be only one file output from a job. The version number is raised by 1 as each section is added to the file. Thus, if the file is at version 1, it contains only 1 section; at version 2 it contains 2 sections; and so forth.

When the job finishes, whether normally or by an abort, the above card will cause the file to be stored. The final version number is then the number of sections written to the file. The only exception to this is that, if a job aborts at the exact moment a section is being added to the file, the file will not be stored at the end of the job.

If it is not desired to store the output file at the end of the job, the above card must be replaced by:

STORE(I=______, V=1-10, T=303, D=2)

The D=2 means the file will not be sent to global store at job termination. All other parameters have the same meaning as before.

****
3.3.2 THE FETCH CARD
****

The following AFM control card is required to read data from a file which has been stored in a previous job:

FETCH(I=______, V=p, T=303)

The I and T parameters are as described in the section on the STORE card. The "V=p" parameter means that the file whose version number is p, and which was stored by a previous job, will be read by this job.

A FETCH card should be used without a STORE card only if no data will be written in the job. In general, this will occur only if ACCUSE is used by itself. Otherwise, the procedures of Section 3.3.3 must be employed.

****
3.3.3 COMBINED USE OF FETCH AND STORE CARDS
****

One FETCH and one STORE card for a file of type 303 may be included in the same job. In this case, the FETCH - STORE pair will cause the data written in a previous job to be used as input and the data written in the new job to be stored.

All information in the fetched file will be written to the stored file. Thus, the final file resulting from such a job will contain (1) all data in the fetched file and (2) all data written during the job.

There are two cases of this kind of job which must be considered.

*****CASE 1.***** A single job is to be submitted which uses data previously written and stores new data.

In this case, the recommended sequence of AFM control cards for file handling is as follows:

```
FETCH(I=a,V=p,T=303,D=4)
STORE(I=a,V="p+1"-"p+10",T=303)
```

In the above, the I parameters set the up-to-20 character file identification of the stored file the same as that of the input file. The V parameters mean version p of the file will be fetched, and the stored file will have a version number somewhere in the range p+1 to p+10. The T parameter is the data type of this type of file. Finally, the D=4 parameter is an AFM requirement allowing special processing of the fetched file.

For example, the cards

```
FETCH(I=TEST FILE,V=4,T=303,D=4)
STORE(I=TEST FILE,V=5-14,T=303)
```

mean that version 4 of TEST FILE will be fetched, and the version number of the stored file will be in the range 5 to 14.

*****CASE 2.***** Several jobs are to be submitted at the same time, all of which fetch the same file, and all of which generate data. This case is complicated by the AFM requirement that no two jobs which will store the same file should be submitted at the same time. OTHERWISE, DATA WILL BE LOST. (The same applies to two jobs which would store any data on the same tape.)

To insure that data will not be lost, the following procedure should be used. One job should be run just as in CASE 1, but the recommended sequence of AFM control cards for any other jobs is as follows:

```
FETCH(I=a,V=p,T=303,D=4)
STORE(I=b,V=1-10,T=303)
```

In the above, the I parameter of the stored file must be different from that of the fetched file. Also, all I parameters of all stored files must be distinct from each other. The version number of the output file will be in the range 1 to 10.

For example, suppose two jobs are to be submitted at the same time, both of which have the AFM control card:

```
FETCH(I=TEST FILE A,V=4,T=303,D=4)
```

Then, two different STORE cards, one in each of the two jobs, might be:

```
STORE(I=TEST FILE A,V=5-14,T=303), and
STORE(I=TEST FILE B,V=1-10,T=303).
```

As noted before, all data in the fetched file will be written to each stored file resulting here in a duplication of sections. To prevent retaining unnecessary data, the PURGE option of the EDFILE program (Appendix A) should be used at the end of jobs to purge duplicate copies of sections. Then, the ADD option may be used in a later job to recombine all data into a single file.

****
3.3.4. SECTION NAMES
****

Each section in a file is assigned a name. This name consists of a 6 - character identification field, followed by a 2 - digit sequence number.

The identification fields currently assigned are:

(1.) BCONDS = boundary conditions.
(2.) OVADIA = ovalities and diameters.
(3.) TSTEPS = time-step information about the elements.

The sequence number is automatically assigned, as each section is written to the file. For instance, the first section of boundary conditions written to the file would be called "BCONDS01", the second "BCONDS02", and so forth. The normal result of a run is the storage of one section of each type with the sequence number of each section being raised by 1 over that of the section of the same type last stored in the file.

Each file is divided into sections, and each section is divided into records. A single record is written at the start of each section of a file. This record contains identification labels, which are printed each time the section is written or read. These labels are:

(1) Job Card Id
(2) User Name
(3) Date
(4) Time
(5) Laboratory
(6) Machine

The subsequent records of each section contain the actual data, collected together in various ways.

****
4. THE ACCUSE PROGRAM
****

****
4.1 INTRODUCTION
****

The ACCUSE program (ACCEPT USER-SELECTED END-RESULTS) provides the primary output capability for ACCEPT. It provides a number of options to selectively print or plot the data produced by ACCEPT.

The recommended mode of operation of ACCUSE is:
(1.) a file of results should be stored at the end of an ACCEPT run, and
(2.) the file of results should then be retrieved in a separate computer run and ACCUSE used to print or plot the results.

This has the following advantages:
(1.) a variety of prints or plots can be obtained at any time without the necessity of redoing the ACCEPT calculations, and
(2.) as new options are made available in ACCUSE, these can be used with the results of previous ACCEPT runs.

A limited amount of time is available at the end of each ACCEPT run, such that ACCEPT and ACCUSE can be used in the same computer run. However, such a run can reach the time limit of the job, and there are possible consequent problems, such as the loss of data.

****
4.2 INPUT DESCRIPTION
****

****
4.2.1 ELEMENT INFORMATION
****

100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. This card is optional. If it is not included, the section in the file of type TSTEPS that was last written to the file will be used as input for this option.

101, 1.0

Inclusion of the above card will result in the following being printed for the edge elements:

(1.) displacements,
(2.) stresses,
(3.) strains,
(4.) plastic strains,
(5.) material property tables, and
(6.) transformation matrices.

The edge elements are the two elements adjacent to the outer surface and to the planes at Z = 0.0, at THETA = 0.0, and at THETA = THETAM (Section 3.1.3).

The displacements are calculated and printed at the nodal points of the elements. The remaining quantities are calculated and printed at the points within the element used for 8-point (2x2x2) Gauss-Legendre quadrature.

The ordering of the Gauss points is as follows (see Figure 4.1). The Gauss points can be visualized as the corner nodes of an element whose sides are parallel to the radial, circumferential, and axial directions. This "Gauss element" is contained within the original element. The first point is the one with the least radial, circumferential, and axial coordinates. Point two is on the edge with point one that extends in the radial direction. Point three is on the edge with point one that extends in the circumferential direction. Point four is on the edge with point three that extends in the radial direction. Points five, six , seven, and eight are on the edges with points one, two, three, and four, respectively, that extend in the axial direction.

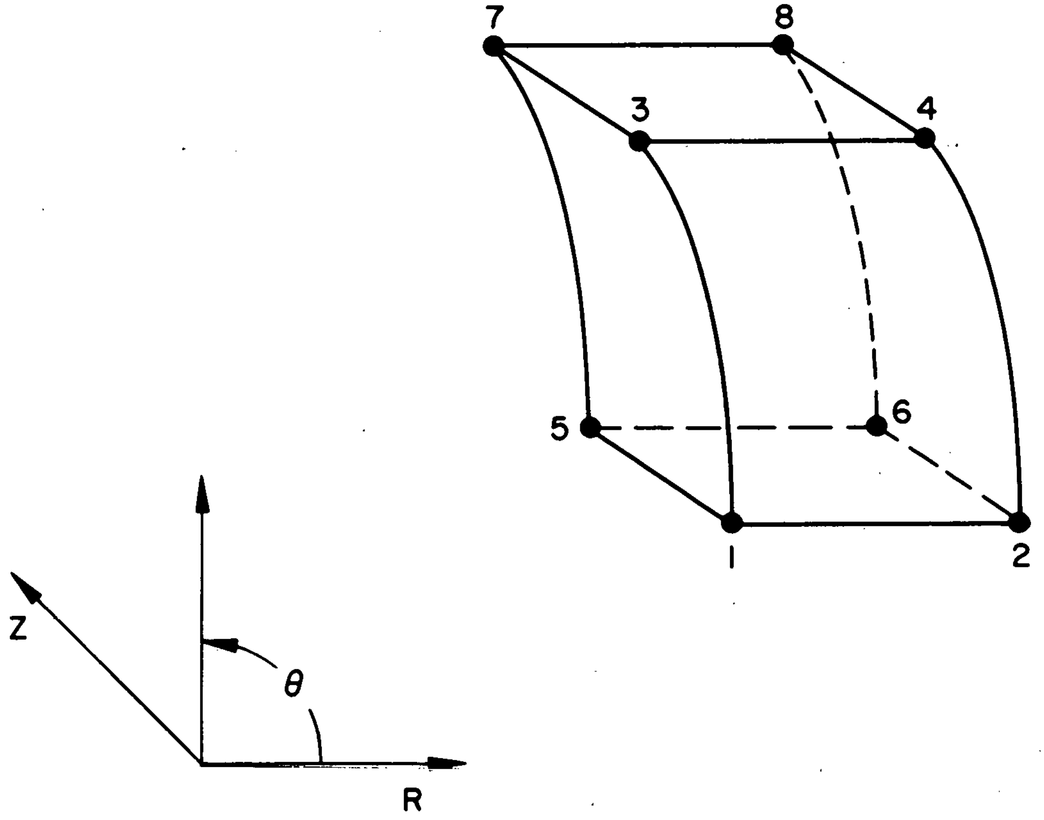


FIGURE 4.1 "GAUSS ELEMENT"

****
4.2.2 CIRCUMFERENTIAL INFORMATION
****

1100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. This card is optional. If it is not included, the section in the file of type TSTEPS that was last written to the file will be used as input for this option.

1101, 1.0

Inclusion of the above card in the input will result in the printing of the coordinates and displacements of the nodes on the outer circumference at Z = 0.0.

****
4.2.3 EDGE INFORMATION
****

2100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. This card is optional. If it is not included, the section of the file of type TSTEPS that was last written to the file will be used as input for this option.

2101, 1.0

Inclusion of the above card in the input will result in the printing of the coordinates and displacements of the nodes along the outer edges in the axial direction. Those on the THETA = 0.0 plane (Section 3.1.3) are printed first, followed by those on the THETA = THETAM plane.

****
4.2.4 THICKNESSES
****

3100. NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. This card is optional. If it is not included, the section in the file of type TSTEPS that was last written to the file will be used as input for this option.

3101. 1.0

Inclusion of the above card in the input will result in the printing of the tube thicknesses at Z = 0.0. These thicknesses are calculated along each radial line of nodes at Z = 0.0. Each thickness is defined as the linear distance of the node on the inner surface to the corresponding node on the outer surface.

For instance, the thickness of the tube along the radial line of nodes at THETA = 0.0 (Section 3.1.3) and Z = 0.0 is the linear distance from node 1 to the node on the outer surface of the tube at THETA = 0.0 and Z = 0.0.

****
4.2.5 SUMMARY EDIT OF OVALITIES AND DIAMETERS
****

4100, NOSECT

If this card is used, section NOSECT (integer) of type TSTEPS will be used as input for this option. For instance, if NOSECT=4, the input section for this option will be TSTEPS04. If this card is omitted, or NOSECT=0, the latest section of type TSTEPS will be used. For instance, if the input file contains sections TSTEPS02 and TSTEPS04, then TSTEPS04 will be used.

4101, NLINE1, NLINE2, ..., NLINELAST

Each entry (integer) on the above card is the number of a line of nodes along element edges around the circumference of the structure. The line of nodes at Z=0.0 is given the number 1. As Z increases, the next line of nodes is given the number 2, and so forth. "Condensed format" may be used for the entries on this card. For instance, the card

4101, 1, 3, -5, 7, -11, -2

requests summary edits to be printed for node lines 1, 3, 4, 5, 7, 9, and 11.

This option should not be used if geometry options 11 or 21 are being used. For the purposes of this edit, all nodes on each node line are assumed to be in the same Z-plane.

Inclusion of the above card in the input will result in the printing of the final summary edit which includes:

(1.) time,
(2.) mid-surface ovality,
(3.) outer-surface ovality,
(4.) average diameter,
(5.) average diameter change,
(6.) average wall thickness, and
(7.) average wall thickness change.

In the case of a 180 degree tube, "outer-surface ovality" is obtained by first finding the circle of least radius that circumscribes all points on the outer surface of the tube. Then, the circle of greatest radius that inscribes all points on the outer surface of the tube, and which has the same center as the first circle, is found. The "outer-surface ovality" is then defined the difference between the diameters of the two circles. In all other cases, "outer-surface ovality" is defined as two times the difference between the maximum and minimum radii from the origin of the coordinate system to points on the outer surface of the tube.

In all cases, "mid-surface ovality" is defined as two times the difference between the maximum and minimum radii from the origin of the coordinate system to points on the mid-surface of the tube. The points on the mid-surface of the tube are those which lie physically halfway between corresponding mesh points on the inner and outer surface of the tube.

The "average diameter" is obtained by adding the maximum and minimum radii, where the maximum and minimum radii are defined as above.

****
4.2.6 SUMMARY EDIT OF BOUNDARY CONDITIONS
****

5100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type BCONDS being used as input for this option. If this card is not included in the input deck, the section of type BCONDS last written to the file will be used as input for this option.

5101, 1.0

Inclusion of the above card in the input will result in the printing of the final summary edit which includes:

(1.) axial loads,
(2.) temperatures, and
(3.) pressure loads.

The above quantities are printed for each table and for each time-step at which data was stored in the ACCEPT run.

****
4.2.7 AXIAL LINES
****

6100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. This card is optional. If it is not included, the section in the file of type TSTEPS that was last written to the file will be used as input for this option.

6101, 1.0

Inclusion of the above card in the input will result in the printing of the coordinates and displacements of all nodes on the outer surface along nodal lines in the Z-direction.

****
4.2.8 OVALITY, DIAMETER, AND THICKNESS PLOTS
****

8100, NOSECT

Inclusion of the above card in an input deck will result in section NOSECT of type TSTEPS being used as input for this option. If this card is not input, the section of type TSTEPS last written to the file will be used for this option.

81cc, IPTYPE, IPAXES, TITLE
where cc = 01 to 99.

Inclusion of this card in an input deck wil result in the creation of plots of mid-surface ovality, outer-surface ovality, change in average diameter, and/or change in average wall thickness versus time.

```
IPTYPE = indicator of plot type (integer).
         (1 = mid-surface ovality.
          2 = outer-surface ovality.
          3 = change in average diameter.
          4 = change in average wall thickness.)

IPAXES = indicator of type of X,Y axes to be used (integer).
         (1 = linear, linear.
          2 = logarithmic, logarithmic.
          3 = linear, logarithmic.
          4 = logarithmic, linear.)

TITLE = up to 30-character plot title (hollerith).
        The title should be enclosed in parentheses on the input card.
```

Data is converted to its absolute value wherever a logarithmic axis is used. Also, any data point for which the abscissa or ordinate is zero is omitted.

In order to use this option, the following AFM control card must be included:

MERGE(I=GRAIL)

Also, the following card must be placed in the control cards immediately following the ACCUSE. card:

REWIND(GRAFIC)

In order to obtain plots on various devices, the above card must then be immediately followed by one of the cards below.

```
(1.) GRAVER. ... to get Versatec plots.   (10 plot limit)
(2.) GRACOM. ... to get microfiche plots. (no plot limit)
(3.) GRACAL. ... to get Calcomp plots.    (no plot limit)
```

****
4.2.9 NODAL POINT EDITS
****

9100, NOSECT

Inclusion of the above card in an input deck will result in the use of section NOSECT of type TSTEPS as input for this option. If this card is not input, the section of type TSTEPS last written to the file will be used for this option.

9101, INDPSS

Inclusion of this card in an input deck will result in the calculation and printing of nodal point plastic strains, total strains, and/or stresses. This will be done for all time-steps for which data was stored in the ACCEPT run.

INDPSS = indicator of types of edits requested.
(1 = plastic strains.
2 = strains.
3 = stresses.
4 = plastic strains, strains.
5 = plastic strains, stresses.
6 = strains, stresses.
7 = plastic strains, strains, stresses.)

The nodal values of each quantity are obtained by first linearly interpolating from the Gauss points (Section 4.2.1) to the nodes of each element. For some elements, the Gauss point values of the quantities can be printed by using the option labelled ELEMENT INFORMATION (Section 4.2.1). One nodal point value is thus obtained for each element containing a node. These values from the elements containing the node are then summed and averaged to obtain the final nodal value of the quantity.

****
4.2.10 DEFORMATION PLOTS
****

Plots of axial or radial deformation profiles are available with ACCUSE. In each case, the original structure is plotted in dashed lines, while the deformed structure is plotted in solid lines.

In order to use either plot option, the following control cards must be included:

```
MERGE(I=GRAIL)
   .
   .
   .
ACCUSE.
```

Then, one of the following cards must be included immediately following the above:

(1) GRAVER. ...to get Versatec plots (10 plot limit).
(2) GRACOM. ...to get microfiche plots (no plot limit).

A. Axial Plots

Plots of axial deformation profiles are available by including the following cards in the ACCUSE input deck.

10100, NOSECT

If this card is used, section NOSECT (integer) of type TSTEPS will be used as input for this option. For instance, if NOSECT=2, the input section for this option will be TSTEPS02. If this card is omitted, or NOSECT=0, the latest section of type TSTEPS will be used. For instance, if the input file contains sections TSTEPS01, TSTEPS02, and TSTEPS03, then TSTEPS03 will be used.

The following cards allow the selection of plots by groups. For each group of plots, a magnification factor may be specified for deformations in the plane of the plot.

101cc, NLINE1, NLINE2, ..., NLINELAST

where cc=01 to ng, ng≤99, and ng=number of requested groups of axial deformation plots.

Each entry (integer) on card 101cc is the number of a line of nodes along element edges down the Z-axis of the structure. The line of nodes at THETA=0.0 is given the number 1. As THETA increases, the next line of nodes is given the number 2, and so forth. "Condensed format" may be used for the entries on this card. For instance, the card

10101, 1, -3, 5

specifies that plots of axial deformation profiles are to be obtained for node lines 1, 2, 3, and 5. One plot is then obtained for each specified line of nodes and for each problem time at which data was saved.

The following card is used to assign magnification factors to the groups of plots.

102cc, DMAGCC

where cc=01 to ng, ng≤99, and ng=number of requested groups of axial deformation plots.

DMAGCC (real) is the magnification factor to be applied to all deformations in the plane of all plots of group cc. DMAGCC defaults to 1.0 if this card is omitted.

If a magnification factor is specified for any group of plots, then a factor must be specified for each group of plots, even if it is 1.0. If present, there must be exactly one entry on each card 102cc. For instance, the card

10201, 2.1

specifies that all deformations for the plots of group 1 are to be magnified by a factor of 2.1.

B. Radial Plots

Plots of radial deformation profiles are available by including the following cards in the ACCUSE input deck.

11100, NOSECT

If this card is used, section NOSECT (integer) of type TSTEPS will be used as input for this option. For instance, if NOSECT=3, the input section for this option will be TSTEPS03. If this card is omitted, or NOSECT=0, the latest section of type TSTEPS will be used. For instance, if the input file contains sections TSTEPS01 and TSTEPS04, then TSTEPS04 will be used.

The following cards allow the selection of plots by groups. For each group of plots, a magnification factor may be specified for all radial deformations.

111cc, NLINE1, NLINE2, ..., NLINELAST

where cc=01 to ng, ng≤99, and ng=number of requested groups of radial deformation plots.

Each entry (integer) on card 111cc is the number of a line of nodes along element edges around the circumference of the structure. The line of nodes at Z=0.0 is given the number 1. As Z increases, the next line of nodes is given the number 2, and so forth. "Condensed format" may be used for the entries on this card. For instance, the card

11101, 2, 5, -9, -2

specifies that plots of radial deformations are to be obtained for node lines 2, 5, 7, and 9. One plot is then obtained for each specified line of nodes and for each problem time at which data was saved.

The following card is used to assign magnification factors to the group of plots.

112cc, DMAGCC

where cc=01 to ng, ng≤99, and ng=number of requested groups of radial deformation plots.

DMAGCC (real) is the magnification factor to be applied to all radial deformations in all plots of group cc. DMAGCC defaults to 1.0, if this card is omitted.

If a magnification factor is specified for any group of plots, then a factor must be specified for each group of plots, even if it is 1.0. If present, there must be exactly one entry on each card 112cc. For instance, the card

11201, 3.35

specifies that all radial deformations for the plots of group 1 are to be magnified by a factor of 3.35.

5. EXAMPLE PROBLEMS

5.1 Internally-Pressurized Thin-Walled Tube

This problem is a long, thin-walled circular tube, subjected to internal pressure. The initial dimensions are inner radius = 0.995 inches and outer radius = 1.005 inches. The time-pressure history is P = 500t psi where 0.0 ≤ t ≤ 1.0 and P = 500 psi where t > 1.0, and t is the time in hours.

The material is 70 percent cold-worked Zircaloy, the temperature is held constant at 700 degrees F, and the tube is open-ended; that is, the stresses in the z-direction are zero.

In order to provide a benchmark against which the ACCEPT solution could be compared, an "exact" large-strain elastic-plastic solution was obtained by first assuming the stresses to be constant across the wall of the tube. This is a good assumption because the wall thickness is small compared to the radius. A set of governing equations was then obtained. The material property routines (Appendix B) were used to calculate the plastic-strain rates, and the governing equations were numerically integrated using a Runge-Kutta method.

The equations governing the "exact" solution are as follows: The stresses in the radial and circumferential directions are assumed to be constant across the wall of the tube and equal to their respective average values obtained by integrating the stresses of the elastic Lame solution to the problem. These stresses are given in terms of the instantaneous pressure P, thickness T, and mid-surface radius R as follows:

$$\sigma_r = -\frac{1}{2} P \left(1 - \frac{1}{2}\frac{T}{R}\right) \qquad (5.1.1)$$

$$\sigma_\theta = P \left(\frac{R}{T} - \frac{1}{2}\right) \qquad (5.1.2)$$

The radial and circumferential strain rates, also assumed constant across the wall of the tube, are given by

$$\dot{\epsilon}_r = \frac{\dot{T}}{T} \qquad (5.1.3)$$

$$\dot{\epsilon}_\theta = \frac{\dot{R}}{R} \qquad (5.1.4)$$

The stress-strain rate relations are:

$$\dot{\epsilon}_r = C_{11}\,\dot{\sigma}_r + C_{12}\,\dot{\sigma}_\theta + \dot{\epsilon}_r^p \qquad (5.1.5)$$

$$\dot{\epsilon}_\theta = C_{12}\,\dot{\sigma}_r + C_{22}\,\dot{\sigma}_\theta + \dot{\epsilon}_\theta^p \qquad (5.1.6)$$

where C_{ij} are the elastic compliance coefficients and $\dot{\epsilon}_i^p$ are the plastic strain rates.

Equations (5.1.1) through (5.1.4) can be used to eliminate the stresses and strain rates from Equations (5.1.5) and (5.1.6). The result is a set of two nonlinear first order ordinary differential equations which govern the variables R and T. These equations were integrated numerically using a fourth order Runge-Kutta routine to solve for the time history of R and T.

The ACCEPT program was then used to solve the same problem. A comparison of the results is given in Figure 5.1 where the change in radius is plotted against time. The solid line shows the "exact" solution and the circles show the ACCEPT solution.

The excellent agreement between the two solutions shows that ACCEPT has correctly solved this large-strain, elastic-plastic problem. Also, it should be noticed that the automatic selection of time-steps by ACCEPT is working quite well, choosing small time-steps during periods when the strain rates are greatest and larger steps when the strains are changing less rapidly.

5.2 Externally Pressurized Hexagonal Shell

This problem is an infinitely long cylindrical shell with a hexagonal cross section, as shown in Figure 5.2. The shell is subjected to an external pressure load and the problem is to find the elastic response to the load.

An approximate elastic solution to the problem can be obtained using thin plate theory. First, the notation that will be used in the plate theory solution is described below.

a = Mid-surface width of the plates which form the hexagonal shell. See Figures 5.2 and 5.3 (5.7600 inches).

b = Outer diameter of shell, measured across the flats. See Figures 5.2 and 5.3 (10.1696 inches).

β = Defined by Equation (5).

C = Defined by Equation (3).

D = Plate bending stiffness, $Et^3/12(1-\nu^2)$ (7732.8 in-lb).

E = Elastic modulus (11.4735×10^6 psi at 530°F).

ν = Poisson's ratio (0.33333).

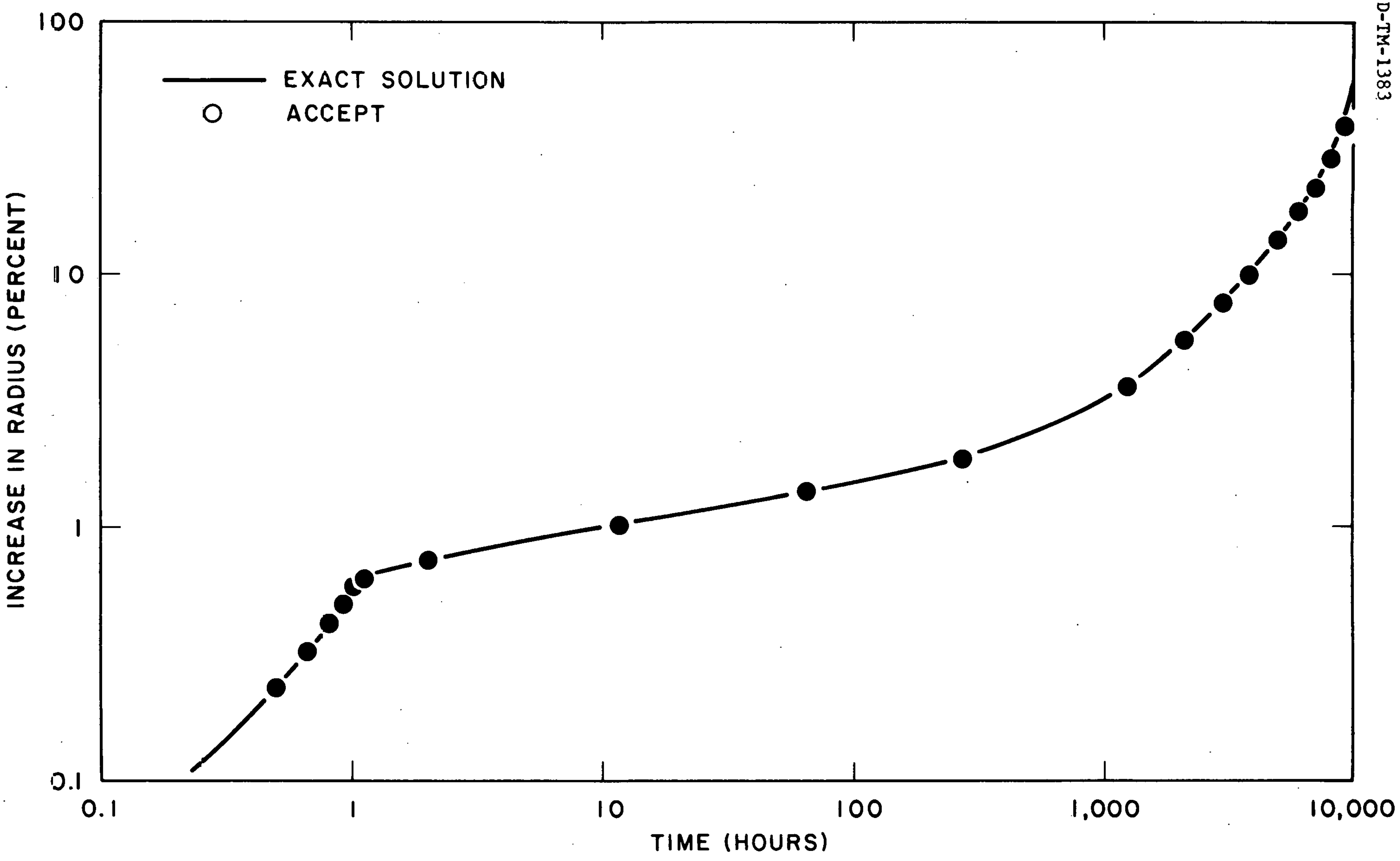


FIGURE 5.1 INCREASE IN RADIUS OF INTERNALLY PRESSURIZED THIN-WALLED TUBE

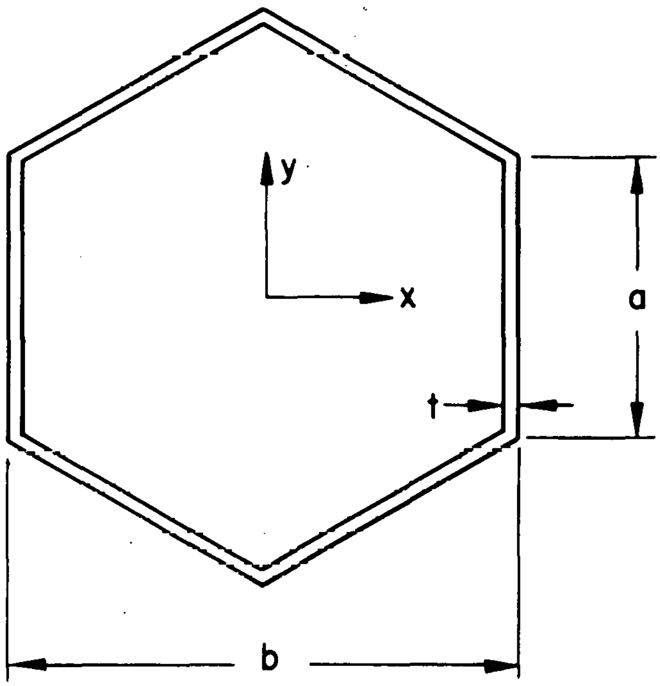


FIGURE 5.2. CROSS-SECTION OF HEXAGONAL SHELL

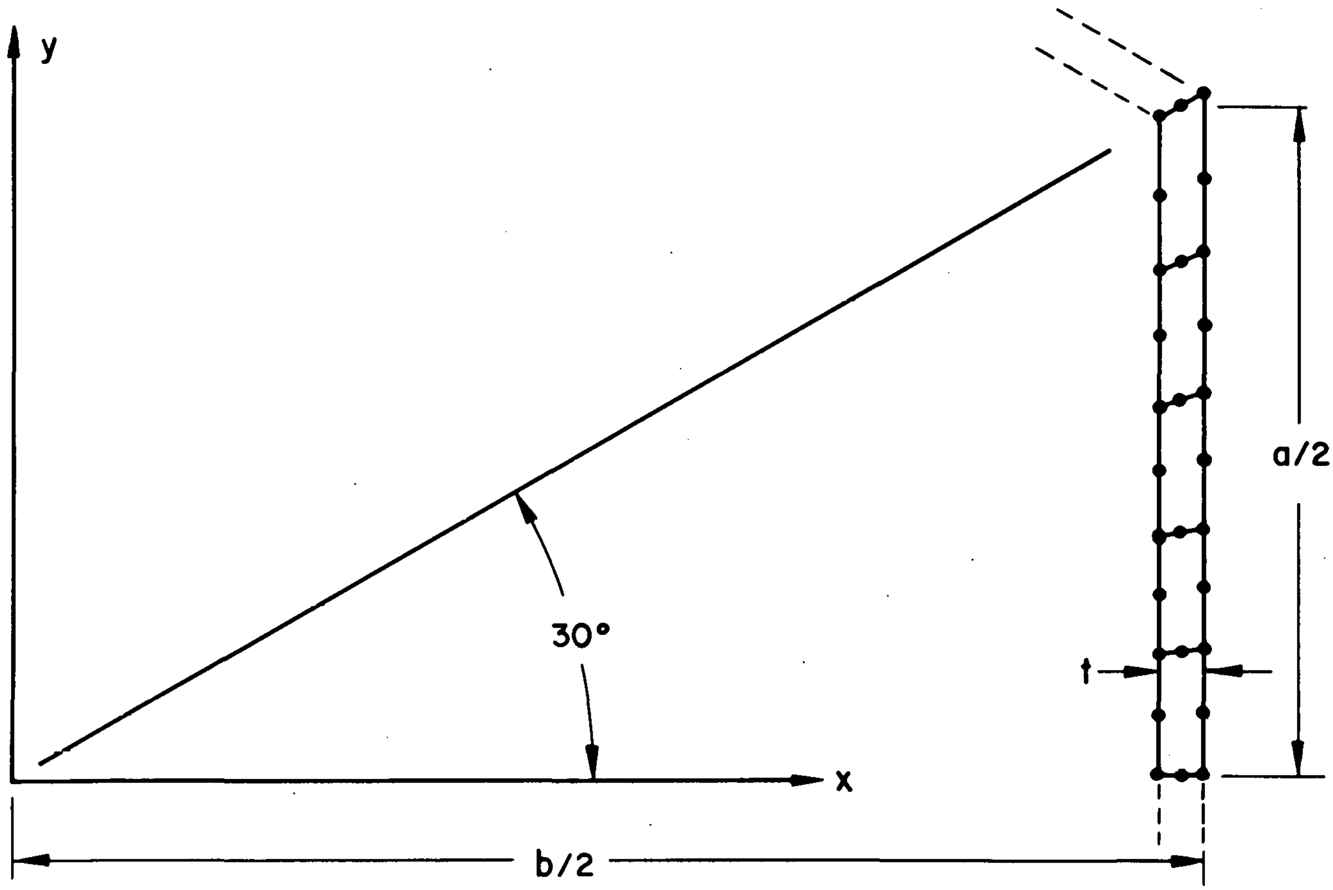


FIGURE 5.3. 5-ELEMENT ACCEPT MESH FOR HEXAGONAL SHELL

N = Membrane force = -Pb/2.

P = Pressure applied to outer surface.

t = Thickness (0.193 inches).

w = Deflection of mid-surface.

x,y = Cartesian coordinates. See Figures 5.2 and 5.3.

The solution to the problem is independent of the axial coordinate; i.e., all cross sections behave in the same fashion. Therefore, the equation governing the deflection is (Reference 6):

$$\frac{d^4w}{dy^4} - \frac{N}{D}\frac{d^2w}{dy^2} = \frac{P}{D} . \qquad (1)$$

The boundary conditions are:

$$w = C \text{ at } y = \pm \frac{a}{2} \qquad (2a)$$

$$\frac{dw}{dy} = 0 \text{ at } y = \pm \frac{a}{2} \qquad (2b)$$

where C is the deflection due to shortening of the plate caused by the (compressive) membrane force and is equal to

$$C = - \frac{Na}{2\ t\ E \tan 30°} = \frac{Pb(b-t)}{4\ t\ E} . \qquad (3)$$

The solution to Equation (1) which satisfies the boundary conditions is:

$$w = \frac{Pa^4}{16\ \beta^3\ D}\left[\frac{\cos(2\beta y/a) - \cos\beta}{\sin\beta}\right] - \frac{Pa^4}{32\ \beta^2\ D}\left[1 - (2y/a)^2\right] + \frac{Pb(b-t)}{4\ t\ E} \qquad (4)$$

where

$$\beta = \sqrt{-Na^2/4D} = \sqrt{Pba^2/8D} . \qquad (5)$$

The deflection at y = 0 is

$$w_o = \frac{Pa^4}{16\ \beta^3\ D}\left[(1 - \cos\beta)/\sin\beta - \beta/2\right] + \frac{Pb(b-t)}{4\ t\ E} . \qquad (6)$$

Equation (6) is plotted in Figure 5.4 along with the ACCEPT results for a 5- and a 10-element mesh. (The 5-element mesh is shown in Figure 5.3.) It should be noted that the plate theory equilibrium equation (Equation (1)) is based on the initial geometry; i.e., small displacements and rotations are assumed. Therefore, the plate theory solution will become more and more inaccurate as the displacements and rotations increase. The theory used in ACCEPT, on the other hand, accounts for finite changes in geometry. Therefore, it is expected that the plate theory and ACCEPT solutions will begin to deviate as the effects of finite changes in geometry become important. This behavior is evident at the high end of Figure 5.4.

5.3 Elastic Collapse of an Imperfect, Pressurized Tube

This problem is an infinitely long, cylindrical tube which is initially slightly out-of-round and is subjected to a pressure load. The initial dimensions are: maximum outside diameter, 2.002 inches; minimum outside diameter, 1.998 inches; thickness, 0.05 inches. The elastic modulus and Poisson's ratio are 10^7 and 0.3, respectively.

The problem was modelled in ACCEPT by using 10 finite elements, evenly spaced over 90 degrees of the circumference. The pressure load P was applied such that P/2 acted on the outside of the tube and -P/2 acted on the inside. This results in an effective pressure P measured per unit area of the mid-surface.

According to the solution given in Reference (7), the ovality, w, (maximum diameter minus minimum diameter) is given by

$$w/w_o = \frac{1}{1-P/P_c} \quad (1)$$

where w_o is the initial ovality and P_c is the critical or collapse pressure which is given by

$$P_c = \frac{E(t/R)^3}{4(1-\nu^2)} \quad (2)$$

where E is the elastic modulus, ν is Poisson's ratio, t is the thickness, and R is the (nominal) mid-surface radius, equal to 0.975 inches.

Equation (1) is plotted in Figure 5.5, along with the ACCEPT solution. The two solutions are in close agreement.

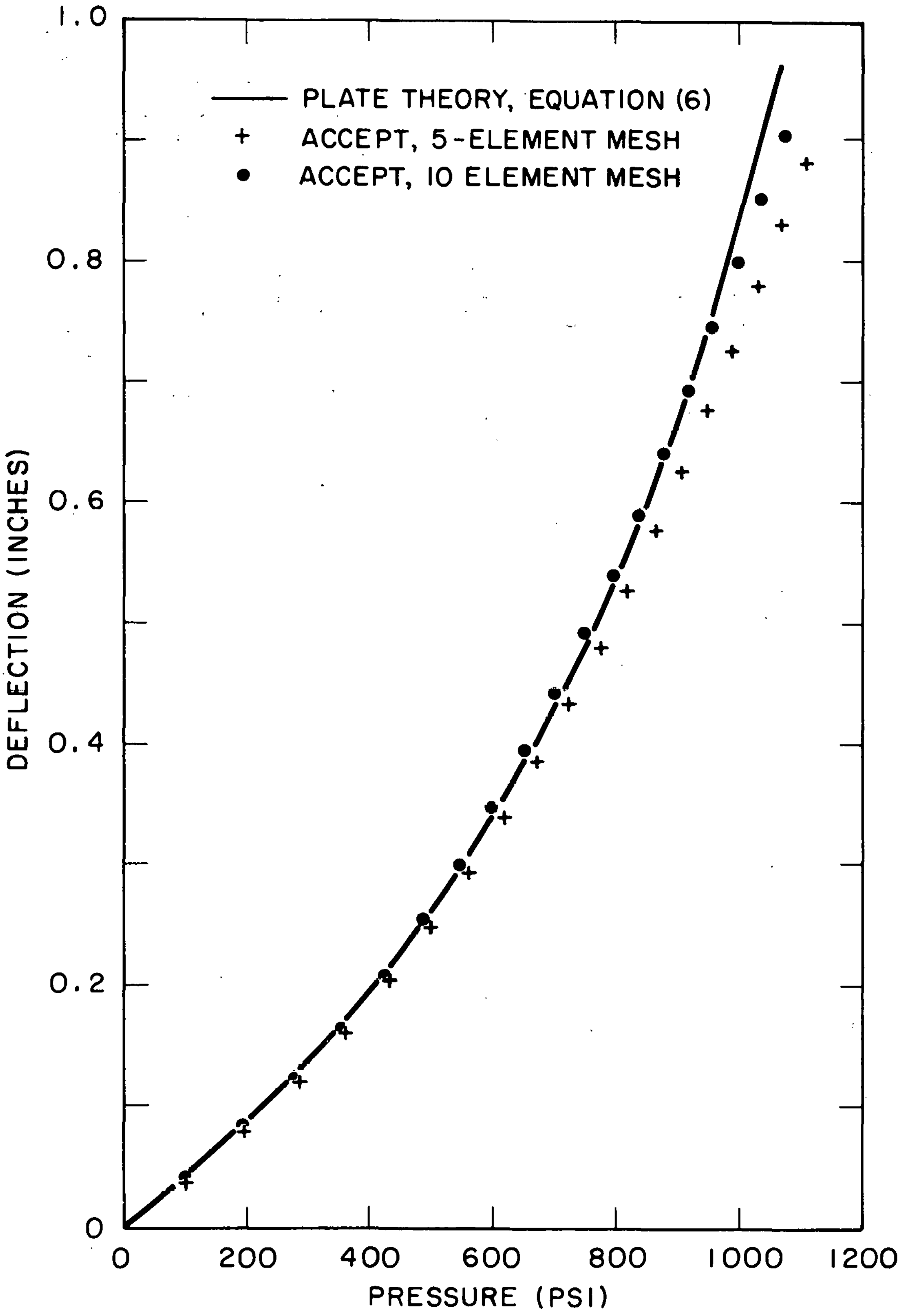


FIGURE 5.4. PRESSURE LOAD VS DEFLECTION AT y=0, ELASTIC HEXAGONAL SHELL

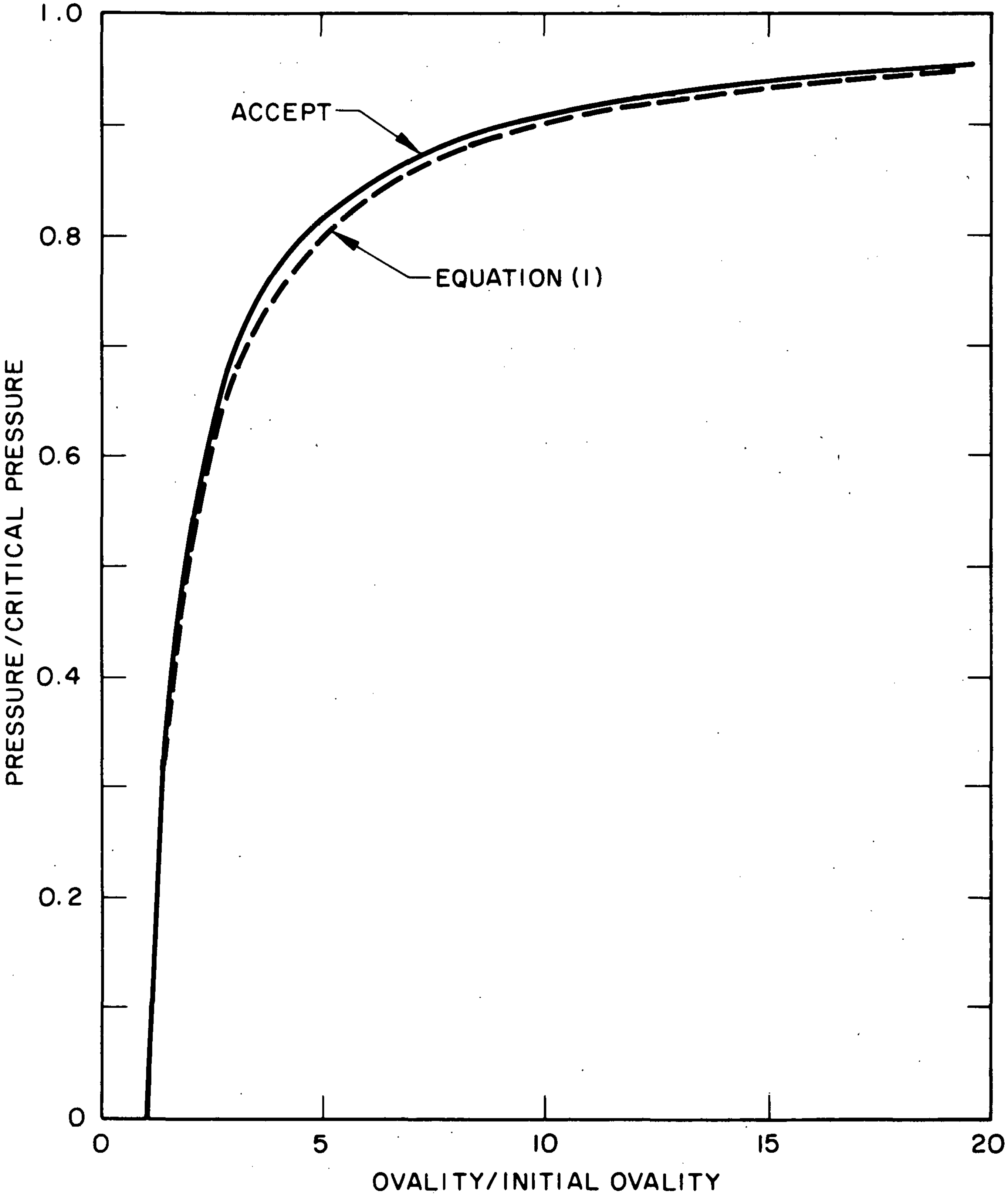


FIGURE 5.5. OVALITY VS PRESSURE FOR AN ELASTIC, IMPERFECT TUBE

5.4 Axial Wrinkling of Fuel Rod Cladding

This problem is designed to simulate the development of an axial wrinkle in the cladding of an externally pressurized reactor fuel rod, as the cladding creeps down and partially contacts the fuel pellets. An axial wrinkle, as illustrated in Figure 5.6, can develop if the initial radial gap between the fuel pellet and the inside of the cladding is sufficiently large such that the cladding cannot completely wrap around the pellet.

A 90-degree circumferential section of the tube was modelled in ACCEPT. It should be noted that the use of a 90-degree model assumes that there are two perpendicular planes of symmetry. This implies the (perhaps unlikely) situation where there are two diametrically-opposed axial wrinkles. The use of a 180-degree model would probably result in the (more likely) situation where only one axial wrinkle becomes fully developed.

The initial dimensions of the cladding were: outside radius at the 0-degree circumferential location, 0.28355 inches; outside radius at the 90-degree location, 0.28345 inches; thickness, 0.027 inches. The radius of the fuel pellet was fixed at 0.2505 inches. This results in an initial radial gap between the fuel pellet and the cladding which varies from 5.95 to 6.05 mils.

The material was recrystallization annealed Zircaloy. The temperature was held constant at 650 degrees F. The pressure was increased from 0 to 2000 psi in a short time span (0.1 hours) and was held constant at 2000 psi thereafter.

The variation of the outside radius along the circumference of the rod is shown in Figure 5.7 for various times during the history of the formation of the axial wrinkle. As time progresses, the axial wrinkle becomes more localized near the 0-degree position.

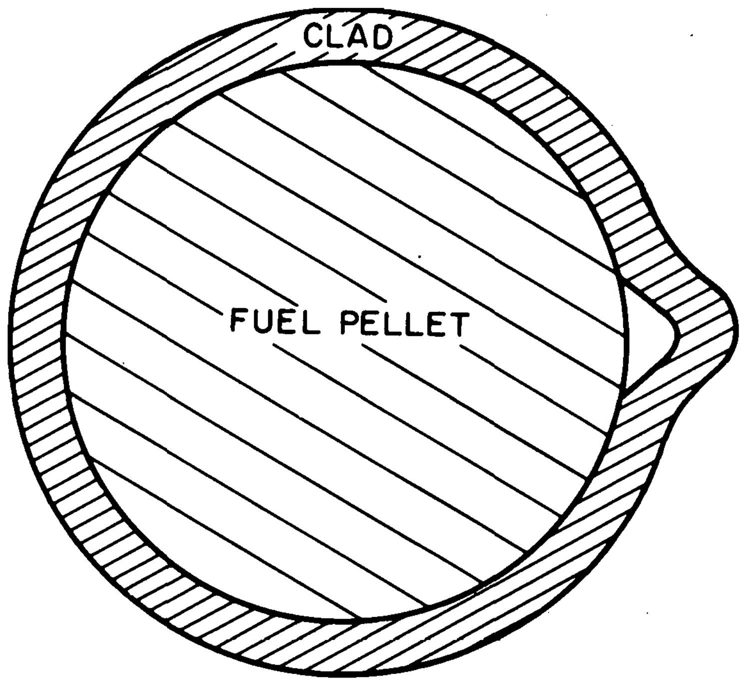


FIGURE 5.6. AXIAL WRINKLE IN FUEL ROD CLADDING

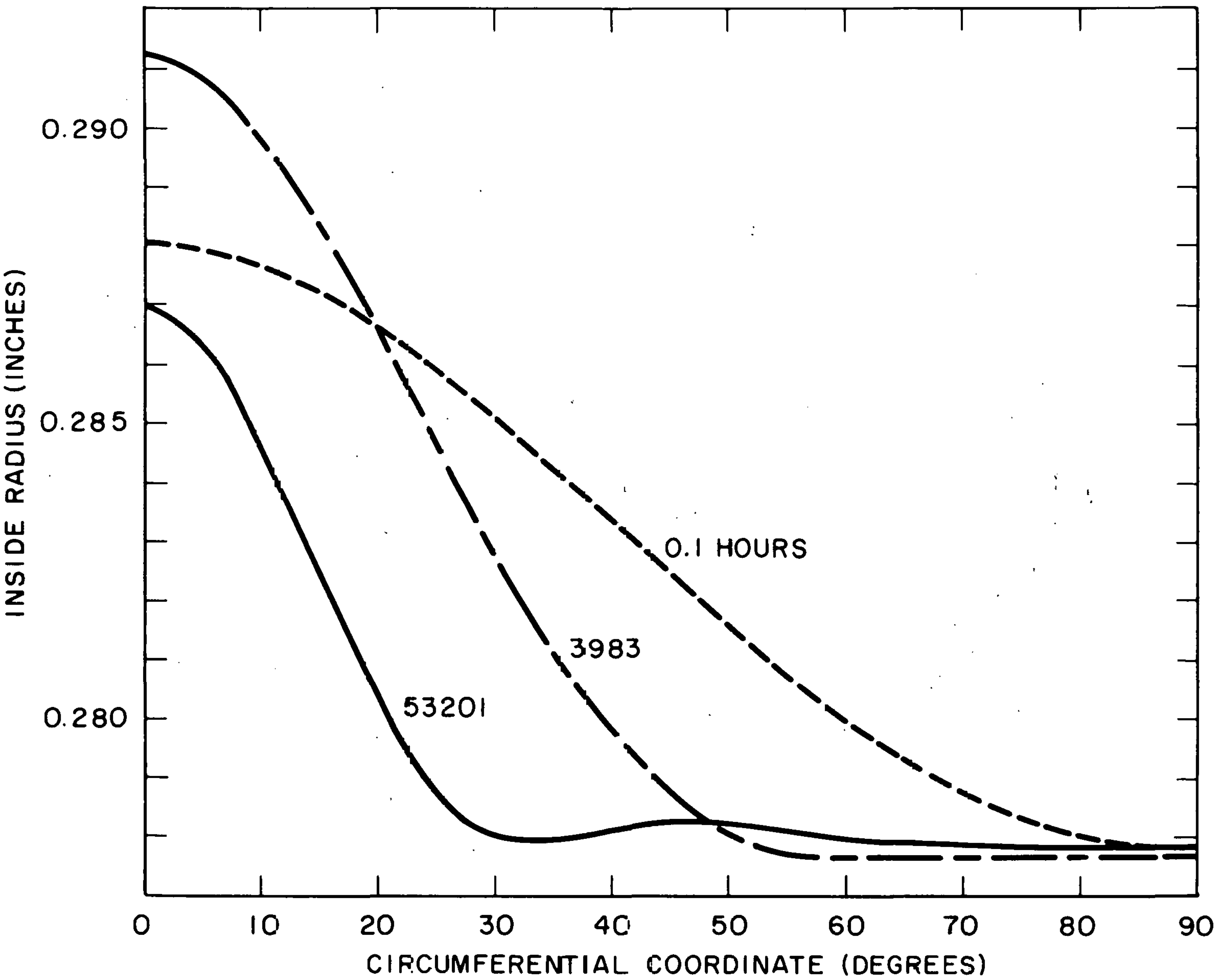


FIGURE 5.7. OUTSIDE RADIUS OF CLADDING DURING FORMATION OF AXIAL WRINKLE

```
        = EXAMPLE PROBLEM 1.  THIN-WALLED TUBE WITH INTERNAL PRESSURE.
        *
        * GEOMETRY CARDS.
        *
0001    10000, 1, 1, 9, 1
0002    11000, .01, 90., 90., 1.005, 1.005, .01, .01
0003    11001, 1, .01
0004    11002, 9, 90.
        *
        * TIME CONTROL CARDS.
        *
0005    20000, 0.
0006    21001,.5,.25,1000.,.05,.05,.05,200.,.01,.01,.01,10.,10.,.1
0007    21002,1.,0.0,1000.,.05,.05,.05,200.,.01,.01,.01,10.,10.,1.
0008    21003,5.,0.0,1000.,.05,.05,.05,200.,.01,.01,.01,10.,10.,10.
        *
        * MATERIAL PROPERTY CARDS.
        *
0009    30000, 1
        *
        * TEMPERATURE CARDS.
        *
0010    40001, 0., 700.
0011    41001, 1, -9
        *
        * PRESSURE LOAD CARDS.
        *
0012    60001, 0., 0., 1., 500.
0013    60002, 0., 0.
0014    61001, 1, -9
0015    61002, 0
0016    62001, 0
0017    62002, 1, -9
        *
        * AXIAL LOAD CARDS.
        *
0018    70000, 0., 0.
        ..........
```

GEOMETRY OPTION INDICATOR =	1
NUMBER OF ELEMENTS THROUGH THE THICKNESS =	1
NUMBER OF ELEMENTS IN CIRCUMFERENTIAL DIRECTION =	9
NUMBER OF ELEMENTS ALONG AXIAL DIRECTION =	1

MAXIMUM AXIAL COORDINATE =	100000-01
MAXINUM CIRCUMFERENTIAL COORDINATE =	900000+02
REFERENCE CIRCUMFERENTIAL COORDINATE =	900000+02
OUTSIDE RADIUS AT THETA = 0. =	100500+01
OUTSIDE RADIUS AT THETA = 90. =	100500+01
THICKNESS AT THETA = 0. =	100000-01
THICKNESS AT THETA = THETA REF. =	100000-01

NUMBER OF ELEMENTS = 9
NUMBER OF NODES = 116

TIME AT START OF PROBLEM = 000000+00

MATERIAL PROPERTY TABLE NUMBER = 1

TABLE ASSIGNMENTS

THE LATER TABLE ASSIGNMENTS OVERLAY EARLIER ASSIGNMENTS.

TABLE	1 OF INSIDE PRESS. LOADS	IS ASSIGNED TO THE FOLLOWING ELEMENTS.							
	1	2	3	4	5	6	7	8	9
TABLE	2 OF OUTSIDE PRESS. LOADS	IS ASSIGNED TO THE FOLLOWING ELEMENTS.							
	1	2	3	4	5	6	7	8	9
TABLE	1 OF TEMPERATURES	IS ASSIGNED TO THE FOLLOWING ELEMENTS.							
	1	2	3	4	5	6	7	8	9

X,Y-COORDINATES OF NODES ON CROSS-SECTION AT Z=0

NODE	X	Y	NODE	X	Y	NODE	X	Y	NODE	X	Y
1	995000+00	000000+00	2	100000+01	000000+00	3	100500-01	000000+00	4	991214+00	867200-01
5	100118+01	875915-01	6	979884+00	172780+00	7	984808+00	173648+00	8	989732+00	174516+00
9	961096+00	257525+00	10	970755+00	260113+00	11	934994+00	340310+00	12	939693+00	342020+00
13	944391+00	343730+00	14	901776+00	420505+00	15	910839+00	424731+00	16	861695+00	497500+00
17	866025+00	500000+00	18	870356+00	502500+00	19	815056+00	570709+00	20	823248+00	576444+00
21	762214+00	639574+00	22	766044+00	642788+00	23	769875+00	646002+00	24	703571+00	703571+00
25	710642+00	710642+00	26	639574+00	762214+00	27	642788+00	766044+00	28	646002+00	769875+00
29	570709+00	815056+00	30	576444+00	823248+00	31	497500+00	861695+00	32	500000+00	866025+00
33	502500+00	870356+00	34	420505+00	901776+00	35	424731+00	910839+00	36	340310+00	934994+00
37	342020+00	939693+00	38	343730+00	944391+00	39	257525-00	961096+00	40	260113+00	970755+00
41	172780+00	979884+00	42	173648+00	984808+00	43	174516-00	989732+00	44	867200-01	991214+00
45	875915-01	100118+01	46	-170655-14	995000+00	47	-171512-14	100000+01	48	-172370-14	100500+01

DISK BUFFER SIZE LOWERED TO 10240 WORDS.

MAXIMUM WAVEFRONT = 74
MAXIMUM NUMBER OF DOF PER GROUP = 24

FIRST WAVEFRONT FILE PLACED IN LCM.

SECOND WAVEFRONT FILE PLACED IN LCM.

```
FIRST TIME-STEP =     250000+00.
CURRENT CHARGE TIME =     3.160 SEC.
****************************************************************************************************


TIME =     250000+00, END PASS       1, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 250000+00 CANDIDATES = 140863+01 212581+01 212317+01 315940+04 372014+04 250000+01 250000+00 205197+01
CURRENT CHARGE TIME = .  6.823 SEC.
****************************************************************************************************


TIME =     500000+00, END PASS       2, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 250000+00 CANDIDATES = 403929+00 208578+01 208322+01 969031+02 116290+03 250000+01 500000+00 260109+01
CURRENT CHARGE TIME =    10.098 SEC.
DATA STORED AT END OF PASS     2.
THE ACCESS NUMBER FOR THIS DATA IS NOSTEP =      1.
****************************************************************************************************


TIME =     750000+00, END PASS       3, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 125000+00 CANDIDATES = 194523+00 187388+01 187171+01 137363+02 183473+02 250000+01 250000+00 650118+00
CURRENT CHARGE TIME =    14.883 SEC.
****************************************************************************************************


TIME =     875000+00, END PASS       4, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 625000-01 CANDIDATES = 122791+00 131647+01 131469+01 368370+01 350244+01 125000+01 125000+00 252249+00
CURRENT CHARGE TIME =    18.309 SEC.
****************************************************************************************************


TIME =     937500+00, END PASS       5, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 625000-01 CANDIDATES = 962995-01 106466+01 106303+01 229092+01 134693+01 625000+00 625000-01 141260+00
CURRENT CHARGE TIME =    22.921 SEC.
****************************************************************************************************


TIME =     100000+01, END PASS       6, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 939591-01 CANDIDATES = 939591-01 975055+00 973596+00 182017+01 116846+01 625000+00 400000+01 114807+01
CURRENT CHARGE TIME =    26.421 SEC.
DATA STORED AT END OF PASS     6.
THE ACCESS NUMBER FOR THIS DATA IS NOSTEP =      2.
****************************************************************************************************


TIME =     109396+01, END PASS       7, OLD TIME-STEP SIZE WAS OK.
```

```
NEXT TIME-STEP = 939591+00 CANDIDATES = 231642+01 225996+01 225636+01 233135+01 970823+00 939591+00 390604+01 194615+01
CURRENT CHARGE TIME =    30.771 SEC.
**********************************************************************************************************************


TIME =     203355+01, END PASS       8, OLD TIME-STEP SIZE WAS OK.
NEXT TIME-STEP = 296645+01 CANDIDATES = 546434+02 764877+01 763969+01 766623+01 942855+01 939591+01 296645+01 972871+01
CURRENT CHARGE TIME =    34.095 SEC.
**********************************************************************************************************************

CURRENT CHARGE TIME =    37.526 SEC.
DATA STORED AT END OF RUN.
THE ACCESS NUMBER FOR THIS DATA IS NOSTEP =     3.
**********************************************************************************************************************
```

SUMMARY EDIT

NOSTEP	TIME	MID-SURFACE OVALITY	OUTER SURFACE OVALITY	AVERAGE DIAMETER	CHANGE IN AVER. DIAMETER	AVERAGE WALL THICKNESS	CHANGE IN AVER. WALL THICKNESS
	000000+00	142109-13	284217-13	201000+01	000000+00	100000-01	000000+00
	250000+00	239601-07	830948-08	201234+01	234332-02	999603-02	-396833-05
1	500000+00	522797-07	206795-07	201473+01	473445-02	999199-02	-800556-05
	750000+00	824905-07	333415-07	201740+01	739922-02	998753-02	-124719-04
	875000+00	103014-06	416632-07	201930+01	929836-02	998440-02	-156033-04
	937500+00	117117-06	484710-07	202047+01	104737-01	998248-02	-175238-04
2	100000+01	131220-06	546000-07	202176+01	117577-01	998039-02	-196124-04
	109395+01	141165-06	595351-07	202259+01	125912-01	997907-02	-209268-04
	203355+01	160398-06	631359-07	202505+01	150548-01	997520-02	-248019-04
3	500000+01	181849-06	683491-07	202763+01	176256-01	997116-02	-288366-04

EDIT OF TIME-STEP VALUES

TIME	TYPE	VALUE	TABLE
250000+00	TEMP.	700000+03	1
250000+00	PRESSURE	125000+03	1
250000+00	PRESSURE	000000+00	2
250000+00	AXIAL LOAD	000000+00	1
500000+00	TEMP.	700000+03	1
500000+00	PRESSURE	250000+03	1
500000+00	PRESSURE	000000+00	2
500000+00	AXIAL LOAD	000000+00	1
750000+00	TEMP.	700000+03	1
750000+00	PRESSURE	375000+03	1
750000+00	PRESSURE	000000+00	2
750000+00	AXIAL LOAD	000000+00	1
875000+00	TEMP.	700000+03	1
875000+00	PRESSURE	437500+03	1
875000+00	PRESSURE	000000+00	2
875000+00	AXIAL LOAD	000000+00	1
937500+00	TEMP.	700000+03	1
937500+00	PRESSURE	468750+03	1
937500+00	PRESSURE	000000+00	2
937500+00	AXIAL LOAD	000000+00	1
100000+01	TEMP.	700000+03	1
100000+01	PRESSURE	500000+03	1
100000+01	PRESSURE	000000+00	2
100000+01	AXIAL LOAD	000000+00	1
109396+01	TEMP.	700000+03	1
109396+01	PRESSURE	500000+03	1
109396+01	PRESSURE	000000+00	2
109396+01	AXIAL LOAD	000000+00	1
203355+01	TEMP.	700000+03	1
203355+01	PRESSURE	500000+03	1
203355+01	PRESSURE	000000+00	2
203355+01	AXIAL LOAD	000000+00	1
500000+01	TEMP.	700000+03	1
500000+01	PRESSURE	500000+03	1
500000+01	PRESSURE	000000+00	2
500000+01	AXIAL LOAD	000000+00	1

****

SECTION OVADIA01 OF FILE TESTFILE VERSION 1, IS WRITTEN WITH THE FOLLOWING LABELS.

```
 JOB CARD ID = IEBWDOC,  USER NAME = WIANC,  DATE =  78/05/11,  TIME =  09.13.07,  LABORATORY = BAPL,  MACHINE = C
*************************


*************************
SECTION BCONDS01   OF FILE TESTFILE            ,  VERSION      2,  IS WRITTEN WITH THE FOLLOWING LABELS.
 JOB CARD ID = IEBWDOC,  USER NAME = WIANC,  DATE =  78/05/11,  TIME =  09.13.08,  LABORATORY = BAPL,  MACHINE = C
AT THE START OF PROCESSING,
THE FOLLOWING SECTIONS ARE IN THE FILE.
 ***** OVADIA01   *****
*************************


*************************
SECTION TSTEPS01   OF FILE TESTFILE            ,  VERSION      3,  IS WRITTEN WITH THE FOLLOWING LABELS.
 JOB CARD ID = IEBWDOC,  USER NAME = WIANC,  DATE =  78/05/11,  TIME =  09.13.11,  LABORATORY = BAPL,  MACHINE = C
AT THE START OF PROCESSING,
THE FOLLOWING SECTIONS ARE IN THE FILE.
 ***** OVADIA01   ***** BCONDS01   *****
*************************
```

```
      = EXAMPLE PROBLEM 2.  HEXAGONAL SHELL TEST PROBLEM.
        *
        *  INFINITE LENGTH
        *  THICKNESS = .193 INCHES
        *  EXTERNAL DIAMETER ACROSS FLATS = 2*5.0848 INCHES
        *  TEMPERATURE = 530 F
        *  MATERIAL = ANNEALED ZIRCALOY
        *  ELASTIC SOLUTION
        *
        * GEOMETRY CARDS.
        *
0001    10000, 11, 1, 10, 1
0002    11000, .2, 30., 30., 5.0848, 0., .193, .193
0003    11001, 1, .2
0004    11002, 10, 30.
        *
        * TIME CONTROL CARDS.
        *
0005    20000, 0.
0006    21001,2000.,50.,200.,.05,/2/ .02,50.,.01,/2/ .005, 50.,1., 10.
0007    23000, 1, 0., 0.
        *
        * MATERIAL PROPERTY CARDS.
        *
0008    30000, 2
0009    32000, 1, 1, 1
        *
        * TEMPERATURE CARDS.
        *
0010    40001, 0., 530.
0011    41001, 1, -10
        *
        * PRESSURE LOAD CARDS.
        *
0012    60001, 0., 0., 2000., 2000.
0013    60002, 0., 0.
0014    61001, 0
0015    61002, 1, -10
0016    62001, 1, -10
0017    62002, 0
        *
        * AXIAL LOAD CARD.
        *
0018    70000, 0., 0.
        ..........
```

```
       = EXAMPLE PROBLEM 3.  ELASTIC BUCKLING.
       *
       *  PRESSURIZED LONG TUBE
       *  SMALL INITIAL OVALITY
       *
       * GEOMETRY CARDS.
       *
0001   10000, 1, 1, 10, 1
0002   11000, .005, 90., 90., 1.001, .999, .05, .05
0003   11001, 1, .05
0004   11002, 10, 90.
       *
       * TIME CONTROL CARDS.
       *
0005   20000, 0.
0006   21001, 1., .02, 250., /3/ .002, 50., /3/ .0005, 10., 1., 10.
       *
       * MATERIAL PROPERTY CARDS.
       *
0007   30000, 1
0008   30014, 1.+7, 0., .3, 0.
0009   32000, 1, 1, 1
       *
       * TEMPERATURE CARDS.
       *
0010   40001, 0., 70.
0011   41001, 1, -10
       *
       * PRESSURE LOAD CARDS.
       *
0012   60001, 0., 0., 1., -500.
0013   60002, 0., 0., 1., 500.
0014   61001, 1, -10
0015   62002, 1, -10
0016   61002, 0
0017   62001, 0
       *
       * AXIAL LOAD CARD.
       *
0018   70000, 0., 0.
       ..........
```

```
        = EXAMPLE PROBLEM 4.  AXIAL WRINKLING PROBLEM.
        *
        *  ANNEALED ZIRCALOY
        *  PRESSURE = 2000 PSI
        *  TEMPERATURE = 650 F
        *  NOMINAL MIDSURFACE RADIUS = 0.27 IN
        *  THICKNESS = 0.027
        *  INITIAL OVALITY = 0.2 MIL
        *  RADIAL GAP = 6 MILS
        *
        * GEOMETRY CARDS.
        *
0001    10000, 1, 1, 12, 1
0002    11000, .03, 90., 90., .28355, .28345, .027, .027
0003    11001, 1, .03
0004    11002, 7, 30., 10, 60., 12, 90.
        *
        * TIME CONTROL CARDS.
        *
0005    20000, 0.
0006    21001, .1, .05, 250., /3/ .01, 50., /3/ .002, 1000., 2., 10.
0007    21002, 50000., /12/ 0.
0008    22000, 0., .1
0009    23000, 1, 0., 0.
        *
        * MATERIAL PROPERTY CARD.
        *
0010    30000, 2
        *
        * TEMPERATURE CARDS.
        *
0011    40001, 0., 650.
0012    41001, 1, -12
        *
        * PRESSURE LOAD CARDS.
        *
0013    60001, 0., 0.
0014    60002, 0., 0., .1, 2000.
0015    61001, 1, -12
0016    62002, 1, -12
0017    61002, 0
0018    62001, 0
        *
        * AXIAL LOAD CARD.
        *
0019    70000, 0., 0., .1, -504.99
        *
        * CONTACT CARDS.
        *
0022    90001, 0., -1.
0023    90101, 0., 1.
0024    90201, 0., .2505
0025    90301, 1
        ..........
```

****
6. ERROR MESSAGES
****

****
6.1. INTRODUCTION
****

ACCEPT does internal checking of input data, input files, and also monitors the progress of the solution. The following is a list of some of the error messages that may be encountered by users together with an explanation of each, the probable cause, and the probable remedy.

The error messages are given below in alphabetic order.

Other error messages are printed by the Bettis Input Package (Reference 5), the FTB data handling package, and various system subroutines.

****
6.2. EXPLANATIONS
****

1. ***** ABORT ***** ----- ----- ARE ASSIGNED TO ELEMENT -----
   WHICH IS NOT A LEGAL ELEMENT NUMBER.
   ***************** TABLE = -----, ELEMENTS ASSIGNED =
   ***************** --

   SITUATION: This error may occur during input, when boundary or other conditions are being assigned to the elements.

   CAUSE: Inside pressure loads, outside pressure loads, or temperatures have been assigned to an element which does not exist. The message prints the number of the table of loads, or temperatures, and the elements to which the table is already assigned. This error will cause an immediate abort.

   REMEDY: Check and correct either the mesh description cards and/or the table assignment cards.

2. ***** ABORT ***** DUE TO INPUT ERRORS.

   SITUATION: This error message may be printed just after all input cards have been read.

   CAUSE: One or more errors have been found in the input cards. After checking all cards, ACCEPT then aborts.

   REMEDY: Find and correct all errors.

3. ***** ABORT ***** FIRST RECORD OF RESTART SECTION DOES NOT MATCH
   PROBLEM BEING SOLVED.
   ***** ABORT ***** IN RECORD, NUMBER OF ELEMENTS = -----, NUMBER OF
   NODES = -----.

   SITUATION: This error may occur when a restart problem is being attempted.

   CAUSE: The probable cause is that the wrong data file has been requested.

   REMEDY: If the number of elements and the number of nodes on the file match those in the current run, then it is likely that the tube geometry parameters input on card 11000 differ from those on the data file. Use the LABELS and PRINT options of the EDFILE program to find the correct file.

4. ***** ABORT ***** LAYER = ----- SPECIFIED ON CARD SERIES 90300 IS OUT OF RANGE.

SITUATION: This error may occur when a contact problem is being solved, and the contact nodes are specified by element layers in the axial direction.

CAUSE: An element layer number used to specify contact nodes is either negative or larger than the number of elements in the axial direction. This will cause an immediate abort.

REMEDY: Check and correct the 903cc cards.

5. ***** ABORT ***** LAYER = ----- SPECIFIED ON CARD SERIES 90400 IS OUT OF RANGE.

SITUATION: This error may occur when a contact problem is being solved and the contact nodes are specified by element layers in the axial direction.

CAUSE: A nodal layer number used to specify contact nodes is either negative or larger than the number of nodes. This will cause an immediate abort.

REMEDY: Check and correct the 904cc cards.

6. ***** ABORT ***** RECORD ----- OF SECTION OF TYPE TSTEPS (or BCONDS) IS OF IMPROPER SIZE = -----.

SITUATION: This error may occur when a restart is being done and the file of restart data is being read.

CAUSE: Either the wrong data file has been requested, or the end of the data file has been reached.

REMEDY: Check to insure the correct file is being used, and that the value of NOSTEPS on card 1000 is correct.

7. ***** ERROR ***** AT LEAST ONE SURFACE HAS NOT BEEN COMPLETELY DESCRIBED.

SITUATION: This error may occur when a contact problem is to be run.

CAUSE: At least one card in series 90ccc, 91ccc, or 92ccc has been supplied. Also, at least one of these series is missing, or there is not the same number of cards in each series.

REMEDY: Supply missing cards.

8. ***** ERROR ***** AT LEAST ONE PRESSURE LOAD TABLE IS MISSING.

SITUATION: This error may occur during input when pressure loads are being defined.

CAUSE: There is at least one card in series 61ccc or 62ccc for which no pressure load table (card in card series 60ccc) has been supplied.

REMEDY: Supply missing table.

9. ***** ERROR ***** CARD 11002 IS MISSING.

SITUATION: This error may occur during input, when the mesh description cards are being read.

CAUSE: Self-explanatory. This error will cause an immediate abort.

REMEDY: Supply card 11002.

10. ***** ERROR ***** CARDS IN ----- SERIES MISSING.

SITUATION: This error may occur during the reading of the input.

CAUSE: The message is printed if a required card series has not been supplied.

REMEDY: Supply missing series.

11. ***** ERROR ***** CONTACT NODES MAY NOT BE SPECIFIED BY BOTH ELEMENT AND NODAL LAYERS.

SITUATION: This error may occur while the input is being read for a contact problem.

CAUSE: Card series 93ccc and 94ccc may not both be used in the same run.

REMEDY: Check cards and specify contact nodes by using strictly either card series 93ccc or series 94ccc by themselves, and never at the same time.

12. ***** ERROR ***** COULD NOT FACTOR TOTAL COMPLIANCE MATRIX.
***** ERROR ***** MATRIX IS SINGULAR.
***** ERROR ***** LOSS OF SIGNIFICANCE IN FACTORIZATION.
***** A RESTART WITH A SMALLER TIME-STEP WILL BE ATTEMPTED.

SITUATION: This error may occur during the back-substitution portion of a time-step.

CAUSE: A solution could not be obtained for the current step because the total compliance matrix relating stress increments to strain increments could not be factored. Either the second or the third part of the message is printed, depending on the reason why the factorization could not be done.

REMEDY: If the restart does not work, check the material properties and the geometry for possible problems.

13. ***** ERROR ITEM ----- ON CARD ----- = ----- IS NEGATIVE, AND THE PREVIOUS ITEM = ----- IS ALSO NEGATIVE.

SITUATION: This error may occur during the reading of an input card that is written in condensed format.

CAUSE: There are three or more consecutive negative items on a condensed format input card.

REMEDY: Check card and correct entries.

14. ***** ERROR ITEM ----- ON CARD ----- = ----- IS OUT OF RANGE.

SITUATION: This error may occur during the reading of an input card that is written in condensed format.

CAUSE: There is an item on a condensed format input card whose absolute value is greater than 50000.

REMEDY: Check card and correct item.

15. ***** ERROR ***** NEED ----- LCM LOCATIONS TO RUN PROBLEM.

SITUATION: This error may occur after the input has been read and before ACCEPT enters the main part of an execution.

CAUSE: The program lacks sufficient LCM to run.

REMEDY: Raise the LCM field length on the job card by the stated (decimal) number of locations. If this is not possible, reduce the size of the problem.

16. ***** ERROR ***** NOT ENOUGH CENTRAL MEMORY TO OUTPUT PRIMITIVE MATRIX.
***** NEED ----- (DECIMAL) LOCATIONS.

SITUATION: This error may occur while ACCEPT is performing a contact problem.

CAUSE: The program lacks sufficient SCM to run.

REMEDY: Raise the SCM field length on the job card by the stated (decimal) number of locations. If this is not possible, reduce the number of contact nodes or the size of the total problem.

17. ***** ERROR ***** NUMBER OF ITEMS ON CARD ------ SHOULD BE EVEN.

SITUATION: This error message may be printed during the input check.

CAUSE: A table, consisting of time-boundary condition pairs, has been input that does not contain an even number of items.

REMEDY: Correct table.

18. ***** ERROR ***** NUMBER OF SECTION = ----- OF TYPE TSTEPS TO BE USED TO RESTART THE PROBLEM IS OUT OF THE RANGE 0 TO 999.

SITUATION: This error may occur while the input for a restart problem is being checked.

CAUSE: The NOSECT parameter on the 1000 card is out of range.

REMEDY: Correct NOSECT, which is the second parameter on the 1000 card.

19. ***** ERROR ***** NUMBER OF TIME-STEP = ----- FROM WHICH INFORMATION IS TO BE USED IN THE RESTARTED PROBLEM IS OUT OF RANGE.

SITUATION: This error may occur while the input for a restart problem is being checked.

CAUSE: The NOSTEP parameter on the 1000 card is either negative or too large. In other words, a set of data that does not exist has been requested from the data file.

REMEDY: Check the NOSTEP parameter printed in the original run in the prints at the end of the time-steps or in the final summary edit of ovalities and diameters. If this is not available, put the data file through option 5 of the ACCUSE program. Correct the NOSTEP parameter. Also, insure the correct file has been obtained.

20. ***** ERROR ***** PARAMETERS THREE TO SIX ON 21000 CARD FOR TIME-INTERVAL ----- MUST BE AT LEAST TWICE PARAMETERS SEVEN TO TEN.

SITUATION: This error may occur when a time-interval is being entered for the first time. If this occurs, an attempt will be made to terminate the program normally and store the data calculated up to this time.

CAUSE: There are 11 entries on the cards in the 21ccc series. Entries 3, 4, 5, and 6 must be at least twice entries 7, 8, 9, and 10, respectively.

REMEDY: Select and enter appropriate parameters on this card.

21. ***** ERROR ***** PRESSURE LOADS MUST BE ASSIGNED ON BOTH THE INSIDE AND THE OUTSIDE OF THE TUBE.

SITUATION: This error may occur during input when pressure loads are being defined.

CAUSE: Either card series 61ccc or card series 62ccc or both are missing.

REMEDY: Supply missing cards.

22. ***** ERROR ***** PROBLEM IS POSSIBLY ILL-CONDITIONED.
***** GROUP = ----- GROUP SIZE = ----- DEGREES-OF FREEDOM WITH PRESCRIBED FORCE = -----.
***** A RESTART WITH A SMALLER TIME-STEP WILL BE ATTEMPTED.

SITUATION: This error is encountered during the forward elimination portion of the solution procedure.

CAUSE: The stiffness matrix is singular or nearly singular. This is possibly due to not specifying displacement boundary conditions sufficient to eliminate the rigid body modes. It can also be due to conditions arising when time-steps are taken that are too large, or when a solution has been obtained that is at or near a buckling load.

REMEDY: If the restart does not work, check for the existence of rigid body modes.

23. ***** ERROR ***** THERE IS NO RECORD IN SECTION ----- OF TYPE BCONDS FOR TIME -----.

SITUATION: This error may occur while the input file for a restart problem is being checked.

CAUSE: There is no record in the boundary condition portion of the restart file for the problem restart time.

REMEDY: Try a resubmittal. If that does not work, check the NOSECT parameter on the 1000 card. If the problem persists, the input file for the restart problem has probably been damaged. As a last resort, use the PRINT option of the EDFILE program to print the contents of the section of type BCONDS.

24. ** ERROR ** TIME AT WHICH RESTART IS REQUESTED IS AT OR BEYOND THE END OF THE LAST TIME-INTERVAL.

SITUATION: This error may occur just after the data has been read from the input file for a restart problem.

CAUSE: The problem time at which the data was stored in the restart file is equal to, or greater than, the time specified on the last card in the 21ccc series.

REMEDY: Alter the cards in the 21ccc series, or lower the value of NOSTEP on the 1000 card.

25. ***** WARNING ***** THIS INPUT SET WAS EMPTY.

SITUATION: This warning may occur while an input card is being read that is supposed to contain integers in condensed format.

CAUSE: A card has been input, for which condensed format is normally used, but which contains no items.

REMEDY: The condensed format input cards should be checked to insure no real problem has occurred. This will not result in an abort.

****
7. VERIFICATION
****

At the time ACCEPT was originally written, several small test problems with predictable solutions were run. Some of these are documented in Section 5. The results were verified by comparison with independent calculations and plots of the "true" solutions.

Since that time, as new features have been added to the program, each has been carefully verified. Also, as problems were solved that simulated pieces of actual tubing, verification has included comparison with test data, and comparison with the results of other computer programs.

****
8. COMPUTER PROGRAM ABSTRACT
****

a. Program Name (and Title):

ACCEPT, A Three-dimensional Finite Element Program for Large Deformation Elastic-Plastic-Creep Analysis of Pressurized Tubes

b. Computer and Language(s):

CDC-6600, CDC-7600, FORTRAN IV, COMPASS

c. Problem Solved:

The ACCEPT program is designed to perform a large deformation elastic-plastic analysis of the three-dimensional time-dependent creep behavior of anisotropic Zircaloy tubes subjected to external pressure (References 1 and 2). In addition, a contact feature allows simulation of such effects as frictionless contact-separation interaction between a fuel rod and fuel pellets. In this case, a user may specify radial gaps, as well as time-varying axial gaps. Also, simulation of the the interaction between a rod and one or more external contact surfaces is permitted. The program also features automatic time-step computation to control the accuracy and numerical stability of a solution. Very large problems can be accomodated. Another feature permits restarting a problem from any point in a previous computer run, together with the possible use of different boundary conditions.

d. Method of Solution:

Large strain theory is used, together with the finite element method, to develop a set of linear equations which are solvable at each time-step for a set of displacement increments. Curved 20-node isoparametric finite elements are used. The stiffness equations are solved by a direct method, called a wavefront method, which takes advantage of the symmetry and sparseness of the stiffness matrix.

e. Restrictions on the Complexity of the Problem:

The following limitations apply to the size of the problems that can be run on the ACCEPT program. The number of nodes is essentially unlimited. The number of elements is limited to 8176, based on the availability of a disk that has a useable space of 30 million 60-bit words. Most practical problems will be run with far fewer elements. The maximum wavefront is limited to 789 if a CDC-6600/7600 Large Core Memory (LCM) is available with at least 262,144 60-bit words. The maximum wavefront is limited to 1100 if an additional 65,536 60-bit words are available in LCM. The above limitations apply to a CDC-7600. In the CDC-6600 version of ACCEPT, all FTB files (Reference 3) that are on disk in the CDC-7600 version are placed in LCM. In this case, problems should not be run with more than 30 elements, and no contact problems should be run.

f. Relationship to Other Programs:

Data is calculated and stored in a File Manager (Reference 3) interface format file. It is then read from this file for restart problems or for post-processing of results by the ACCUSE program.

g. Typical Running Time:

The following examples indicate the current running time of ACCEPT.

1. A problem with 20 elements (1 radial by 5 circumferential by 4 axial elements), 188 nodes, and 22 contact nodes required 7.7 seconds per step.
2. A problem with 25 elements (1 by 5 by 5), 222 nodes, and 79 contact nodes required 11 seconds per step.
3. A problem with 35 elements (1 by 5 by 7), 308 nodes, and 96 contact nodes required 18.1 seconds per step.
4. A problem with 45 elements (1 by 5 by 9), 388 nodes, and 107 contact nodes required 18.3 seconds per step.

All the above runs were made on a CDC-7600 at 140K SCM and 1000K LCM. To obtain times for a CDC-6600, the above times should be multiplied by a factor of 4.5.

h. References:

1. D.N. Hutula and B.E. Wiancko, "ACCEPT: A Three-Dimensional Finite Element Program for Large Deformation Elastic-Plastic Analysis of Creep Collapse of Externally Pressurized Tubes", WAPD-TM-1383, March, 1980.
2. D.N. Hutula, "Finite Deformation Analysis of Continuum Structures with Time-Dependent Anisotropic Elastic - Plastic Material Behavior", WAPD-TM-1384, March, 1980.
3. W.R. Cadwell, Editor, "Reference Manual - Bettis Programming Environment", WAPD-TM-1181 (1974).

i. Unusual Features of the Program:

ACCEPT has an automatic computation of the size of time-steps. A number of critical loops have been programmed in the CDC assembly language COMPASS. A restart option allows the user to calculate and store data and then restart the problem at any point at a later date.

j. Status:

In production use.

k. Machine Requirements:

The SCM size should be at least 65K and the LCM size should be at least 1000K. The program utilizes up to six disks transferring in parallel.

l. Operating System:

SCOPE 3.3 (CDC-6600) / SCOPE 2.0 (CDC-7600)

m. Other Programming, Restrictions, or Operating Information:

The required software environment is described in Reference 3. It includes routines for program loading, free-field input conversion and processing, storage and retrieval of "permanent" File Manager files, scratch input/output, storage allocation, and plotting. All files used for communication with other jobs are in File Manager format. Fortran IV statements equivalent to the assembly language statements are included as comments in all COMPASS subroutines.

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9. REFERENCES
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2. D.N. Hutula and B.E. Wiancko, "MATUS: A Three-Dimensional Finite Element Program for Small-Strain Elastic Analysis", WAPD-TM-1081, March 1973.

3. O.C. Zienkiewicz, B.M. Irons, J. Ergatoudis, S. Ahmad, F.C. Scott, "Iso-Parametric and Associated Element Families for Two and Three-Dimensional Analysis", in "Finite Element Methods in Stress Analysis", I. Holand and K. Bell, Editors, TAPIR, Technical University of Norway, Trondheim, 1969.

4. Y.C. Fung, "Foundations of Solid Mechanics", Prentiss-Hall, 1965.

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

6. S.P. Timoshenko and S. Woinowsky-Krieger, "Theory of Plates and Shells", Second Edition, McGraw-Hill, New York, 1959, Chapter 12.

7. S.P. Timoshenko and J.M. Gere, "Theory of Elastic Stability", McGraw-Hill, New York, 1961, Section 7.5.

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10. ACKNOWLEDGMENTS
****

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APPENDIX A
EDFILE, A FILE EDITING PROGRAM TO PROCESS SECTIONED INTERFACE FORMAT FILES OF TYPE 303

****
A.1 INTRODUCTION
****

The EDFILE program supplies file editing capabilities to the user of sectioned interface format files of type 303. See Reference 5 for an explanation of interface format files and of the Advanced File Manager (AFM). The capabilities are as follows: (1) print the labels of all sections of a file (LABELS option), (2) print the contents of any section (PRINT option), (3) purge any section (PURGE option), and (4) add any section from one file to another file (ADD option).

****
A.2 INPUT DESCRIPTION
****

The input to EDFILE is divided into 4 parts, each of which corresponds to one of the 4 capabilities. Each part, in general, consists of (1) an option selection card, (2) card(s) identifying the file(s) to be processed, (3) a card specifying the number of sections to be processed, and (4) card(s) naming the sections to be processed.

The input is arranged by option groups so that any option, or combination of options, may be used on any entry into EDFILE. The input is always ended by an input card with STOP in the first 4 columns.

INPUT CHECK LIST

TITLE OF CARD	LIST OF VARIABLES	FORMAT
LABELS CARD 1	IMOPT, INFILE	A6, I6
LABELS CARD 2	IMFILE, IMVERN	A24, I6
PRINT CARD 1	IMOPT, INFILE	A6, I6
PRINT CARD 2	IMFILE, IMVERN	A24, I6
PRINT CARD 3	NOSECT	I6
PRINT CARD 4	NAME1,...,NAME6	6A12
PURGE CARD 1	IMOPT, INFILE	A6, I6
PURGE CARD 2	IMFILE, IMVERN	A24, I6
PURGE CARD 3	NOSECT	I6
PURGE CARD 4	NAME1,...,NAME6	6A12
ADD CARD 1	IMOPT, INFILE	A6, I6
ADD CARD 2	IMFIL1, IMVER1	A24, I6
ADD CARD 3	IMFIL2, IMVER2	A24, I6
ADD CARD 4	NOSECT	I6
ADD CARD 5	NAME1,...,NAME6	6A12

****
A.3 LABELS OPTION
****

This option is used to print the labels of all sections of a file. It requires the designation of an input file by input cards.

LABELS CARD 1.
Format: A6,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMOPT	1-6	Put in the left-adjusted word LABELS. This selects the option to print the labels of each section in the file.
2. INFILE	7-12	Indicator: 0 = the input file is the file of type 303 last FETCHed, or written, in the current job. 1 = the input file is the file of type 303 designated on LABELS CARD 2.

If INFILE = 0 on LABELS CARD 1, the following card should not be included in the input. If a single file has been FETCHed, and no file has previously been written in the job, INFILE = 0 may be used to print the labels of the FETCHed file. Also, INFILE = 0 may be used to print the labels of the last file written in the job, such as the output file of the PURGE or ADD option.

LABELS CARD 2.
Format: A24,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMFILE	1-24	File id (left-adjusted) of the type 303 whose section labels are to be printed. (I parameter on AFM card)
2. IMVERN	25-30	Version number of the above file. (V parameter on AFM card)

****
A.4 PRINT OPTION
****

The PRINT option is used to print the contents of any or all sections of an interface format file of type 303. This option is intended only to permit a user to determine the contents of a section in case of bookkeeping problems. It is not intended to replace edits available in the programs which create the data. Descriptions of each section of a file are contained in Section 4.

Each word of each set of each section is printed twice - in integer and real format (I6,E10.3). To conserve paper, an abbreviated edit is also available.

PRINT CARD 1.
Format: A6,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMOPT	1-6	Put in the left-adjusted word PRINT. This selects the option to print the contents of any section(s) of the file.
2. INFILE	7-12	Indicator: 0 = the input file is the file of type 303 last FETCHed, or written, in the current job. 1 = the input file is the file of type 303 designated on PRINT CARD 2.

If INFILE = 0 on PRINT CARD 1, the following card should not be included in the input. If a single file has been FETCHed, and no file has previously been written in the job, INFILE = 0 may be used to print the contents of sections of the FETCHed file. Also, INFILE = 0 may be used to print the sections from the last file written in the job, such as the output file of the PURGE or ADD option.

PRINT CARD 2.
Format: A24,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMFILE	1-24	File id (left-adjusted) of the file of type 303 whose sections are to be printed. (I parameter on AFM card)
2. IMVERN	25-30	Version number of the above file. (V parameter on AFM card)

PRINT CARD 3.
Format: I6

VARIABLE	COLUMNS	DESCRIPTION
NOSECT	1-6	Indicator: < 0 means do an abbreviated print of the (-NOSECT) sections given on PRINT CARD 4. = 0 means do an abbreviated print of all sections. > 0 means do a full print of the NOSECT sections given on PRINT CARD 4.

The following card should not be included in the input if NOSECT = 0 on PRINT CARD 3. If NOSECT is not equal to 0, the following card should be included as many times as necessary to name all sections whose contents are to be printed.

PRINT CARD 4.
Format: 6A12

VARIABLES	COLUMNS	DESCRIPTIONS
1. NAME1	1-12	These are the (left-adjusted) names of the sections whose contents are to be printed. (See Section 4.)
2. NAME2	13-24	
. . .	. . .	
6. NAME6	61-72	

If a section to be printed does not exist in a file, the message "***** WARNING ***** SECTION ____ WAS NOT FOUND IN FILE ____, VERSION ____." is printed, and the program continues.

****
A.5 PURGE OPTION
****

This option is used to purge sections from an interface format file of type 303. It requires the designation of 2 files, which are used in the manner:

FILE2 = FILE1 - (purged sections)

The sections to be retained are copied from the input file (FILE1) to the output file (FILE2). The sections of FILE1 which are to be retained keep their original names in FILE2. For example, suppose FILE1 contains sections "BCONDS01", "BCONDS02", and "BCONDS03". If "BCONDS02" is to be purged, FILE2 will contain sections "BCONDS01" and "BCONDS03" with a gap in the numbering of the mesh data sections.

FILE1 is designated by an AFM STORE card. This means the STORE card is required for this option. The version number of FILE2 is incremented by 1 for every use of the PURGE option.

If this option successfully writes FILE2, then FILE1 is no longer available in this job.

PURGE CARD 1.
Format: A6,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMOPT	1-6	Put in the left-adjusted word PURGE. This selects the option to purge any section(s) of a file.
2. INFILE	7-12	Indicator: 0 = FILE1 is the file of type 303 last FETCHed, or written, in the current job. 1 = FILE1 is the file of type 303 designated on PURGE CARD 2.

If INFILE = 0 on PURGE CARD 1, the following card should not be included in the input deck. If a single file has been FETCHed, and no file has been previously written in the job, INFILE = 0 may be used to purge sections from the FETCHed file. Also, INFILE = 0 may be used to purge sections from the last file written in the job, such as the output file of the PURGE or ADD option.

PURGE CARD 2.
Format: A24,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMFILE	1-24	File id (left-adjusted) of FILE1. (I parameter on AFM card)
2. IMVERN	25-30	Version number of FILE1. (V parameter on AFM card)

It may sometimes be desired to store only the data most recently generated in a job. For example, suppose a production run is made in which it is desired to keep only the data generated by the last program executed in the job. The following card allows for this possibility, in that EDFILE may be used at the end of a job to purge all but the last few sections of a file. The following card also allows for the normal case of purging sections from a file.

PURGE CARD 3.
Format: I6

VARIABLE	COLUMNS	DESCRIPTION
NOSECT	1-6	Indicator: < 0 means purge all but the last (-NOSECT) sections of the entire file. = 0 means purge all but the last two sections of the file. > 0 means purge NOSECT sections from the file, the names of which are to be designated on PURGE CARD 4.

The following card should not be included in the input deck unless NOSECT > 0 on PURGE CARD 3. If NOSECT > 0, PURGE CARD 4 should be included as many times as necessary to name all sections to be purged from FILE1.

PURGE CARD 4.
Format: 6A12

VARIABLES	COLUMNS	DESCRIPTIONS
1. NAME1	1-12	These are the names (left-adjusted) of the sections which are to be purged. (See Section 4.)
2. NAME2	13-24	
.	.	
.	.	
.	.	
6. NAME6	61-72	

If a section to be purged does not exist in the input file, the message "***** WARNING ***** SECTION ____ WAS NOT FOUND IN FILE ____, VERSION ____."

is printed, and the program continues. If no sections were purged, the message

"***** WARNING ***** NO SECTIONS PURGED. OUTPUT FILE NOT WRITTEN."

is printed, and the program continues. In this case, the output file is not written since it would only be a duplicate of the input file.

However, it is regarded as an error situation if the result of all purges would be an empty file. In this case, the messages

"***** ERROR ***** PURGE WOULD EMPTY FILE _____, VERSION _____."
"SECTIONS IN FILE ARE AS FOLLOWS." "SECTIONS TO BE PURGED ARE AS FOLLOWS."

are printed, along with the lists of the sections in the file and those to be purged. The program then aborts, prior to any purges.

****
A.6 ADD OPTION
****

This option is used to add any section from one file of type 303 to another file of type 303.

The ADD option requires the designation of 3 files, which are used in the manner:

FILE3 = FILE1 + FILE2.

All sections of the first file (FILE1) will be written to the output file (FILE3), and these sections will retain their original names in FILE3. Some or all of the sections of the second file (FILE2) will be written to FILE3, and the names of these sections will be adjusted with reference to the names of the sections from FILE1. For instance, if FILE1 has a section named "BCONDS01", this section will also be called "BCONDS01" in FILE3. If FILE2 has a section also named "BCONDS01", which is to be written to FILE3, the name of this section will be adjusted to be "BCONDS02" in FILE3. Whenever a name change occurs, an informative message will be printed.

FILE1 and FILE2 are designated by input cards. FILE3 is always designated by an AFM STORE card. This means the STORE card is required in order to use this option. The version number of the file to be stored is incremented by 1 for every use of the ADD option.

FILE1 is no longer available in this job if FILE3 is successfully written.

ADD CARD 1.
Format: A6,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMOPT	1-6	Put in the left-adjusted word ADD. This selects the option to add sections from one file to another file.
2. INFILE	7-12	Indicator: 0 = FILE1 is the file of type 303 last FETCHed, or written, in the current job. 1 = FILE1 is designated on ADD CARD 2.

If INFILE = 0 on ADD CARD 1, the following card should not be included in the input.

ADD CARD 2.
Format: A24,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMFIL1	1-24	File id (left-adjusted) of FILE1. (I parameter on AFM card)
2. IMVER1	25-30	Version number of FILE1. (V parameter on AFM card)

The following card must always be included in the input to the ADD option. It designates FILE2, which must have been FETCHed.

ADD CARD 3.
Format: A24,I6

VARIABLES	COLUMNS	DESCRIPTIONS
1. IMFIL2	1-24	File id (left-adjusted) of FILE2. (I parameter on AFM card)
2. IMVER2	25-30	Version number of FILE2. (V parameter on AFM card)

ADD CARD 4.
Format: I6

VARIABLE	COLUMNS	DESCRIPTION
NOSECT	1-6	Indicator: < 0 means add last (-NOSECT) sections from FILE2 to make FILE3. = 0 means add all sections from FILE2 to make FILE3. > 0 means add NOSECT sections from FILE2 to make FILE3. (The sections to be added are designated on ADD CARD 5.)

The following card should not be included in the input unless NOSECT > 0 on ADD CARD 4. If NOSECT > 0, ADD CARD 5 should be included as many times as necessary in order to name all sections to be taken from the second input file.

ADD CARD 5.
Format: 6A12

VARIABLES	COLUMNS	DESCRIPTIONS
1. NAME1	1-12	These are the (left-adjusted) names of the sections to be taken from FILE2 and written to FILE3. (See Section 4.) A name may change when the corresponding section is written to FILE3.
2. NAME2	12-24	
. . .	. . .	
6. NAME6	61-72	

If a section to be taken from FILE2 is not present in that file, the message

"***** WARNING ***** SECTION ____ WAS NOT FOUND IN FILE ____, VERSION ____."

is printed, and the program continues. If no section is taken from FILE2, the message

"***** WARNING ***** NO SECTION TAKEN FROM FILE _____, VERSION _____. OUTPUT FILE NOT WRITTEN."

is printed; FILE3 is not written; and the program continues.

WP 80-211/0229

Zircaloy Material Model

W. J. Duffin
S. P. Fidelman

B. 1. INTRODUCTION

The strain increment computed for a point in a time interval Δt is

$$\begin{aligned}\Delta \varepsilon_{ij} = {} & \Delta \varepsilon_{ij} \text{ (thermal expansion)} \\ & + \Delta \varepsilon_{ij} \text{ (elastic)} \\ & + \Delta \varepsilon_{ij} \text{ (thermal creep).}\end{aligned} \tag{1}$$

Contributions to the strain increment are computed for the average value of temperature during the time step or, in the case of thermal expansion, for the temperature difference during the time step. Thermal expansion is independent of stress. The last two strain contributions on the right in Equation (1) depend on the stress and use the estimated average value in the time step.

These strain contributions depend on the state of the Zircaloy as well. Material states are described by tables of parameters internal to ACCEPT. At present there are two tables for 70 percent cold worked and annealed Zircaloy-4. Changes of material state that occur during the course of a problem are followed internally.

B. 2. TEXTURE

In the following description the coordinate system used to describe stress, strain, and other directional quantities is imbedded in the material. Direction 1 is the radial, direction 2 is the circumferential, and direction 3 the axial directions of the tube. Zirconium and its Zircaloys have a close packed hexagonal crystal structure below about 1550°F. The metal in the tube consists of aggregates of single crystal grains and any preferential alignment of these grains in a particular direction will cause an anisotropy in the properties of the metal. If the axes of the crystal grains were all parallel the metal would exhibit the anisotropy of a hexagonal single crystal. If the individual grains are randomly oriented the metal would be isotropic. Texture is the term used to denote the particular distribution of individual crystal grain orientations within the metal. Quantitatively texture is described by the texture factors f_1, f_2, and f_3 where

$$f_i = \sum \nu_i \, Cos^2 \phi_i \; ; \qquad (2)$$

ν_i is the volume fraction of crystal grains with C axis, the axis normal to the hexagonal symmetry plane, oriented at angle ϕ_i to the i axis in the material. Texture factors have the property that

$$f_1 + f_2 + f_3 = 1 \qquad (3)$$

Averages of these quantities are provided in the property tables or can be supplied by the user. They are required to determine thermal expansion.

B. 3. THERMAL EXPANSION

The strain arising purely from temperature change can be estimated from the response of a single crystal (1):

$$\varepsilon_P = 2.153 \times 10^{-6} (T-32) + 8.083 \times 10^{-9} (T-32)^2 - 3.287 \times 10^{-13} (T-32)^3$$

and

$$\varepsilon_N = 3.962 \times 10^{-6} (T-32) + 1.164 \times 10^{-9} (T-32)^2 + 3.906 \times 10^{-13} (T-32)^3 , \quad (4)$$

where ε_P and ε_N are the thermal expansion in the hexagonal plane and normal to it respectively at T degrees Fahrenheit. Thermal strain in the directions of the imbedded coordinate i is

$$\varepsilon_i = \varepsilon_P (1-f_i) + \varepsilon_N f_i \quad (5)$$

where f_i is the texture factor for the i^{th} direction. The thermal expansion strain increment is the difference for this quantity computed at the beginning and end of the time step.

B. 4. ELASTIC STRAIN

Elastic strain increments are computed directly from the imposed stress with the option of either isotropic or orthotropic elastic constants.

a. Isotropic constants depend linearly on temperature. Coefficients for Young's modulus, Poisson's ratio, and the reference temperature are provided in the tables for

$$E = E_0 + E_T\ (T-T_R) \quad \text{and} \tag{6a}$$

$$\nu = \nu_0 + \nu_T\ (T-T_R)\ , \tag{6b}$$

where E_0 is nonzero and $T_R = 0$. The shear modulus and modulus of volume expansion are computed from

$$G = E/2(1 + \nu) \tag{7a}$$

$$K = E/3(1 - 2\ \nu)\ . \tag{7b}$$

b. If $E_0 = 0$ in Equation (6a), ACCEPT uses orthotropic elastic constants. The orthotropic constants C_{ij} where

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{23} \\ \varepsilon_{31} \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{bmatrix} \tag{8}$$

also depend linearly on temperature

$$C_{ij} = C^0_{ij} + C^T_{ij}\ (T-T_R)\ , \tag{9}$$

where $T_R = 650°F$. The matrices C^0_{ij} and C^T_{ij} are provided in ACCEPT or may be input.

B. 5. CREEP STRAIN

The creep strain is given by

$$\dot{\varepsilon}_C = \dot{\varepsilon}_0 . \tag{10}$$

$\dot{\varepsilon}_0$ is the thermal rate.

A. This rate is a generalized rate, a scalar independent of coordinates or direction in the material. The creep equation is expressed in terms of generalized stress and strain. The thermal rate is

$$\dot{\varepsilon}_0 = \dot{\varepsilon}_0 (\sigma_0, \varepsilon_0, T) \tag{11}$$

where σ_0 and ε_0 and $\dot{\varepsilon}_0$ are the thermal generalized stress, strain, and strain rate. T is the temperature. The generalized rates are related to the strain rate components by requiring that ($\dot{\varepsilon}_0 \cdot \sigma_0$) be the rate of creep work,

$$\dot{W}_0 = \dot{\varepsilon}_0 \sigma_0 = \sum_{ij} (\dot{\varepsilon}^0_{ij} \sigma_{ij}). \tag{12}$$

The strain rate components are

$$\dot{\varepsilon}^{o}_{kl} = \dot{\varepsilon}_{o} \frac{\partial \sigma_{o}}{\partial \sigma_{kl}} = \dot{\varepsilon}_{o} \; D^{o}_{kl} \tag{13}$$

where the $D^{o}_{kl} = \partial \sigma_{o} / \partial \sigma_{kl}$ are the thermal flow directors. The generalized stress is related to the stress components by

$$\sigma_{o} = \sum_{ij} D^{o}_{ij} \; \sigma_{ij} \; . \tag{14}$$

The generalized stress is defined as

$$\sigma_{o} = \frac{1}{K \; (P \; (R \; +1))^{1/2}} \{ R \; (\sigma_1 - \sigma_2)^2 + R \, P \; (\sigma_2 - \sigma_3)^2 + P \; (\sigma_3 - \sigma_1)^2$$

$$+ A \; \sigma^2_{23} + B \; \sigma^2_{13} + C \; \sigma^2_{12} \}^{1/2} \tag{15}$$

Quantities R and P provide the measure of directional anisotropy in the material. The value of P in compression is calculated from

$$P_c = P'_c + (P''_c - P'_c) \; [1-\exp(-k' \; \varepsilon_{o})] \tag{16}$$

where $P_c^{'}$, $P_c^{''}$, $k^{'}$ are constants. A set of A, B, C values is input to define the shear stress dependence of creep. In an isotropic material, R=P=1, A=B=C=3, and K=1. ACCEPT provides K, R, and P (including $P_c^{'}$, $P_c^{''}$, $k^{'}$) or K, R, and P may be set by the user. The A, B, C values may be input by the user, or ACCEPT will calculate default values as follows:

$$\text{A default} = \left(\frac{1}{K_c}\right)^2 \frac{6\,R_c}{R_c + 1} \tag{17}$$

$$\text{B default} = \left(\frac{1}{K_c}\right)^2 \frac{6}{R_c + 1} \tag{18}$$

$$\text{C default} = \left(\frac{1}{K_c}\right)^2 \frac{6\,R_c}{P_c\,(R_c + 1)} \tag{19}$$

where R_c, P_c, and K_c are the values of R, P, and K for the "compressive" state ($\sigma_2 < \sigma_1$ and $\sigma_3 < \sigma_1$). When K, R, and P differ in tension and compression, their values in multiaxial stress systems are interpreted as follows:

1. Tension $\sigma_2 \geq \sigma_1$ and $\sigma_3 \geq \sigma_1$ use tension values of R (R_T), P (P_T), and K (K=1).

2. Compression $\sigma_2 < \sigma_1$ and $\sigma_3 < \sigma_1$ use compression values of R (R_c), P (P_c), and K (K_c).

3. Mixed $\sigma_1 + \sigma_2 + \sigma_3 > 3\,\sigma_3$ interpolate with

$$K = \frac{|\sigma_1 - \sigma_2|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} + K_c \frac{|\sigma_1 - \sigma_3|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} \tag{20}$$

and

$$(R \text{ or } P) = \frac{(R_T \text{ or } P_T)\, |\sigma_1 - \sigma_2|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} + \frac{(R_C \text{ or } P_C)\, |\sigma_1 - \sigma_3|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} . \tag{21}$$

4. Mixed $\sigma_1 + \sigma_2 + \sigma_3 < \sigma_3$ interpolate with

$$K = \frac{|\sigma_1 - \sigma_3|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} + K_c \frac{|\sigma_1 - \sigma_2|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} \tag{22}$$

and

$$(R \text{ or } P) = \frac{(R_T \text{ or } P_T)\, |\sigma_1 - \sigma_3|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} + \frac{(R_C \text{ or } P_C)\, |\sigma_1 - \sigma_2|}{|\sigma_1 - \sigma_2| + |\sigma_1 - \sigma_3|} \tag{23}$$

B. Thermal Creep - Thermal creep is based on a constant stress creep curve shown schematically in Figure 1. Initially there is a transient region with a time dependence of strain of

$$\varepsilon_0 = At^n \tag{24}$$

followed by a steady state region where strain rate is independent of strain.

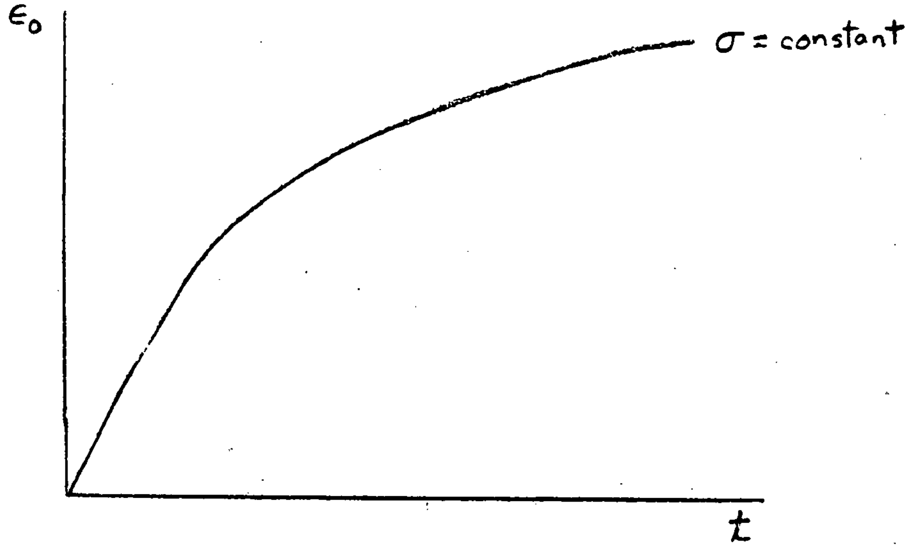


Figure 1

Thermal Strain Versus Time at Constant Stress

Strain dependence of the transient creep rate at constant stress is

$$\dot{\varepsilon}_o(tr) = S\ \varepsilon^q \qquad (25)$$

where

$$S = n\ A^{1/n} \qquad (26a)$$

and

$$q = 1 - 1/n \qquad (26b)$$

The overall thermal rate is

$$\dot{\varepsilon}_0 = \text{Max} \begin{cases} \dot{\varepsilon}_0(tr) \\ \dot{\varepsilon}_0(ss) \end{cases} . \quad (27)$$

Stress dependencies of the transient, at constant strain, and steady state rates are

$$\dot{\varepsilon}_0(tr) = F \sinh m \ \sigma_0 \quad (28)$$

and

$$\dot{\varepsilon}_0(ss) = a \ \sigma_0^b . \quad (29)$$

Temperature dependence of the thermal rate at constant stress and strain is

$$\dot{\varepsilon}_0 = B \exp(-Q/kT) \quad (30)$$

where B is a constant, k Boltzmann's constant, T the absolute temperature, and Q an activation energy. If, for given stress and strain, the thermal rate is known at two temperatures, T_1 and T_2, the rate at an intervening or nearby temperature T is

$$\ln \dot{\varepsilon}_0(T) = \ln \dot{\varepsilon}_0(T_1) + \frac{\frac{1}{T_1} - \frac{1}{T}}{\frac{1}{T_1} - \frac{1}{T_2}} \ln \frac{\dot{\varepsilon}_0(T_2)}{\dot{\varepsilon}_0(T_1)} . \quad (31)$$

Transient thermal creep is specified in the ACCEPT tables by giving the values of S and q in Equation (25) at two stresses, σ_1 and σ_2, at each of three temperatures, T_1, T_2, and T_3. These two transient stress levels are set such that $\sigma_2 = 2\ \sigma_1$. Steady state creep is specified by giving the steady state rate at two stresses at these temperatures.

The thermal rate is computed by:

1. Converting the coefficients in Equations (25) and (29) in the tables to values for the temperature of interest. If T lies between T_1 and T_2 then

$$q(T) = q(T_1) + (\tau - \frac{\alpha}{T}) [q(T_2)-q(T_1)] , \quad (32a)$$

$$S(T) = S(T_1) \left[\frac{S(T_2)}{S(T_1)}\right]^{(\tau - \frac{\alpha}{T})} , \quad (32b)$$

$$\ln a(T) = \ln a(T_1) + (\tau - \frac{\alpha}{T}) \ln \frac{a(T_2)}{a(T_1)} , \quad (32c)$$

and $$b(T) = b(T_1) + (\tau - \frac{\alpha}{T})\,[b(T_2)-b(T_1)]\ , \qquad (32d)$$

where $$\tau = \frac{T_2}{T_2-T_1} \quad \text{and} \quad \alpha = \frac{T_1\,T_2}{T_2-T_1}\ .$$

This gives the S and q at stresses σ_1 and $\sigma_2 = 2\sigma_1$ at the temperature T.

2. At strain ε the transient rate is given by Equation (25) and

$$\frac{\dot{\varepsilon}_t(\sigma_2,\ \varepsilon)}{\dot{\varepsilon}_t(\sigma_1,\ \varepsilon)} = \frac{S_2\ \varepsilon^{q_2}}{S_1\ \varepsilon^{q_1}} = \frac{\sinh m\,2\,\sigma_1}{\sinh m\,\sigma_1} = 2\cosh m\,\sigma_1 \qquad (33)$$

giving m and F at arbitrary strains, exact solutions are

$$m(\varepsilon, T) = \frac{1}{\sigma_1}\ln\,(X + (X^2 - 1)^{1/2}) \text{ where} \qquad (34a)$$

$$X = \frac{1}{2}\,\frac{S_2}{S_1}\ \varepsilon^{(q_2-q_1)} \quad \text{and}$$

$$F(\varepsilon, T) = S_1\ \varepsilon^{q_1}/\sinh\,[m(\varepsilon, T)\ \sigma_1]\ . \qquad (34b)$$

In the present ACCEPT material tables $\dot{\varepsilon}(\sigma_2) \gg \dot{\varepsilon}(\sigma_1)$ in the strain range of interest and the exponential approximation to the sinh is used $(X \gg 1)$ giving

$$m(\varepsilon, T) = \frac{1}{\sigma_1} \ln \left(\frac{S_2}{S_1} \varepsilon^{(q_2 - q_1)}\right) \quad (35a)$$

$$F(\varepsilon, T) = \frac{2S^2{}_1}{S_2} \varepsilon^{(2q_1 - q_2)} . \quad (35b)$$

3. Quantities S and q can be determined at arbitrary stress by selecting two strain levels ε_1 and ε_2. Then

$$\dot{\varepsilon}_t(2) = F(\varepsilon_2, T) \sinh [m(\varepsilon_2, T)\ \sigma] = S(\sigma, T)\ \varepsilon_2^{q(\sigma, T)} \text{ and}$$

$$\dot{\varepsilon}_t(1) = F(\varepsilon_1, T) \sinh [m(\varepsilon_1, T)\ \sigma] = S(\sigma, T)\ \varepsilon_1^{q(\sigma, T)} . \quad (36)$$

Solving Equations (36) for S and q gives

$$q(\sigma,T) = \ln[\dot{\varepsilon}_t(2) / \dot{\varepsilon}_t(1)] / \ln[\varepsilon_2/\varepsilon_1] \tag{37a}$$

and

$$\ln S(\sigma,T) = \ln \dot{\varepsilon}_t(1) - q(\sigma, T) \ln \varepsilon_1 . \tag{37b}$$

In this manner at the temperature of interest the strain rate at arbitrary constant stress

$$\dot{\varepsilon}_t(\sigma, \varepsilon, T) = S(\sigma,T)\ \varepsilon^{q(\sigma,T)} \tag{38}$$

and the rate at arbitrary constant strain

$$\dot{\varepsilon}_t(\sigma, \varepsilon, T) = F(\varepsilon,T) \sinh[m(\varepsilon,T)\ \sigma] \tag{39}$$

can be determined.

4. Steady state creep is described by the power law

$$\dot{\varepsilon}_{ss} = a\ \sigma^{b} \tag{40}$$

5. The final thermal rate is the maximum of the steady state or transient rates.

6. The Creep Compliance Matrix. The increment of creep occurring in a time step is

$$\Delta\ \varepsilon^{C}_{ij} = \int_{t}^{t+\Delta t} \dot{\varepsilon}^{C}_{ij}\ dt + \frac{1}{2} \sum_{kl} \int_{t}^{t+\Delta t} \dot{C}_{ijkl}\ (\text{creep})\ dt\ \Delta\ \sigma_{kl}\ , \tag{41}$$

where the integrands are evaluated at the average temperature of the time step and at the stress state of the beginning of the time step. The elements of the creep compliance matrix are

$$\dot{C}_{ijkl} = \frac{\partial\ \dot{\varepsilon}_{ij}}{\partial\ \sigma_{kl}} = \frac{\partial}{\partial\ \sigma_{kl}}\ \dot{\varepsilon}_{o} \frac{\partial\ \sigma_{o}}{\partial\ \sigma_{ij}} \tag{42}$$

In terms of the flow directions, Equation (13),

$$\dot{C}_{ijkl} = \dot{\varepsilon}_0 \frac{\partial D^o_{ij}}{\partial \sigma_{kl}} + D^o_{kl} D^o_{ij} \frac{\partial \dot{\varepsilon}_o}{\partial \sigma} . \quad (43)$$

B. 7. INPUT

The property cards 30JCC provide the user access to the ACCEPT property tables. J takes values 0 to 8 and refers to property table J+1. Cards 30J01 through 30J06 contain the input for thermal creep. The keyword following the card number indicates the temperature and state of the material, e.g., TMP1UN for T_1 unirradiated material; the entries in the matrix prim(i) are

Prim(i)

i	entry
1	T_1(°F)
2	σ_1(psi) thermal generalized stress
3	S_1(hr^{-1}) } coefficients of Equation (25) at σ_1
4	q_1
5	0
6	0
7	σ_2=2 σ_1(psi)

8 $S_2 (hr^{-1})$ } coefficients of Equation (25) at $\sigma_2 = 2\ \sigma_1$
9 q_2

10 0

11 0

12 σ_x(psi) } stress and steady state strain rates used to determine a and b in Equation (29)
13 $\dot{\varepsilon}_{ss}(\sigma_x)(hr^{-1})$
14 σ_y(psi)
15 $\dot{\varepsilon}_{ss}(\sigma_y)\ (hr^{-1})$

Cards 30J07 and 30J08 give the values of R and P in tension and compression to compute the generalized stresses with Equation (15). For example, in tension

rth - thermal R for σ_0 .

pth - thermal P for σ_0 .

Card 35ccc may be used to input the values of A, B, and C which are used in Equation (15).

Card 30J09 gives the value of K in Equation (15) for the generalized stress σ_0.

Card 30J10 contains coefficients for the various creep terms

egmin = minimum strain at which transient thermal rate is computed in Equation (25).

Card 30J12 contains the texture factors f_i.

Card 30J14 contains the isotropic elastic constants of Equation (6).

Cards 30J15 and 30J16 contain the matrices C^{o}_{ij} and C^{T}_{ij} of Equation (9), respectively. These are the coefficients for the orthotropic elastic constants.

REFERENCES

1. J. J. Kearns, "Thermal Expansion and Preferred Orientation in Zircaloy", WAPD-TM-472, November 1965.

2. F. A. Nichols, "Theory of the Creep of Zircaloy During Neutron Irradiation", Journal of Nuclear Materials, 30, 1969, pp. 249-270.

APPENDIX C
ALTERNATE MESH DEFINITIONS

****
C.1 INTRODUCTION
****

In this appendix, mesh definition capabilities alternate to that defined in Sections 2.3.4 and 3.1.3 are described.

The geometry of a cross-section is defined by the same parameters used in Section 2.3.4, with the following interpretations:

THETAM = maximum circumferential coordinate. Equal to 180/N, where N = 3,4,5,... is the number of sides of the polygon.

THETAR = reference circumferential coordinate used to specify thickness variations.

R0 = distance from origin of coordinate system to outside of tube at THETA = 0 degrees.

R90 = not applicable.

T0 = thickness of tube at THETA = 0 degrees.

TREF = thickness of tube at THETA = THETAR.

The above parameters apply to the equilateral polygon cross-section. If the irregular polygon cross-section option is used, only THETAM is used in the program.

****

If either of these options is used, the prints and plots of ovalities, diameters, and thicknesses, and of the changes in these quantities, do not apply and should not be used.

****

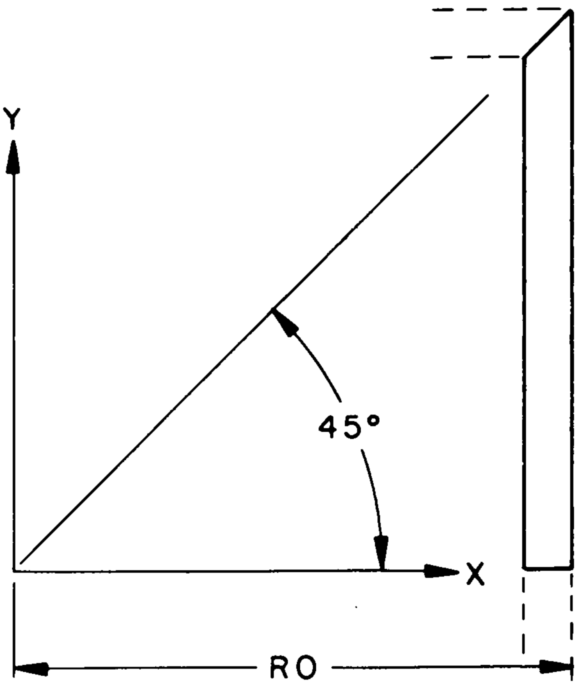
****
C.2 EQUILATERAL POLYGON CROSS-SECTION
****

Figure C.1 shows examples of cross-sections of tubes with mid-surfaces in the form of equilateral polygons. When this geometry option is invoked, the finite element mesh is constructed over only one-half of one of the sides, as shown in the figure. Thus, it is assumed that the planes of geometric symmetry are also planes of symmetry with respect to the loads, temperatures, etc. More generality can be achieved by using the irregular polygon option described in Section C.3.

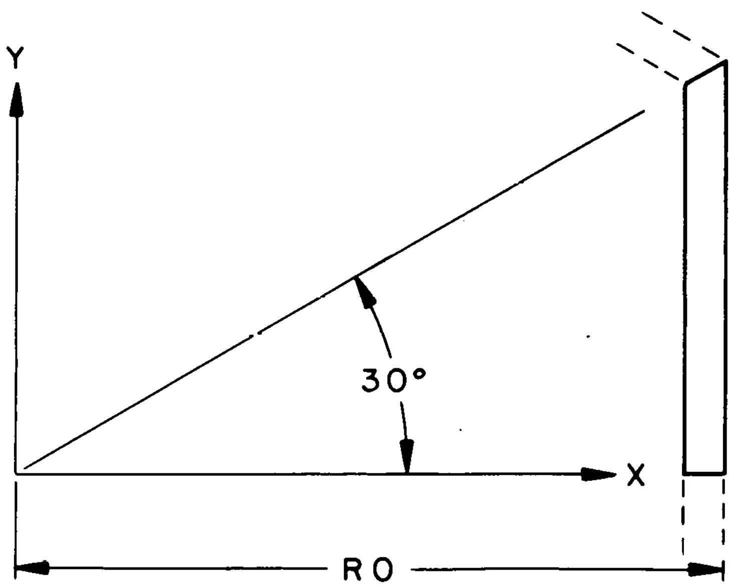
The thickness, measured in the direction normal to the mid-surface, is computed from the formula given in Section 2.3.4.

The finite element mesh is constructed such that the circumferential boundaries between elements are THETA = constant planes. The element spacing in the thickness direction is uniform, while the element spacings in the circumferential and axial directions can be specified arbitrarily.

This option can be invoked by setting INDGEM = 11 on card 10000 (Section 3.1.3).



a. SQUARE CROSS-SECTION



b. HEXAGONAL CROSS-SECTION

FIGURE C.1 EXAMPLES OF CROSS-SECTIONS OF TUBES WITH EQUILATERAL POLYGON MID-SURFACES, SHOWING THE REGION OVER WHICH THE MESH IS GENERATED

****
C.3 IRREGULAR POLYGON CROSS-SECTION
****

Figure C.2 shows an example of a cross-section of a tube with a mid-surface in the form of an irregular polygon. The cross-section is defined by the X, Y coordinates of the corner points where the sides intersect. Straight lines are drawn between the corner points to construct the inner and outer walls of the tube. An arbitrary number of sides can be specified.

The element spacing is uniform in the thickness and circumferential directions for a given side, while the element spacing in the axial direction can be specified arbitrarily. The uniform circumferential element spacing can be overridden by dividing a side into a number of shorter sides.

This option is invoked by setting INDGEM = 21 on card 10000 (Section 3.1.3). The following cards must also be used in this option.

12101, INCLOS (OPTIONAL)

This card may be used to indicate (INCLOS = 1) that the cross-section being defined is closed, i.e., it is a 360 degree cross-section. If this card is not included, the default case (INCLOS = 0) is assumed, which means the cross-section is not closed.

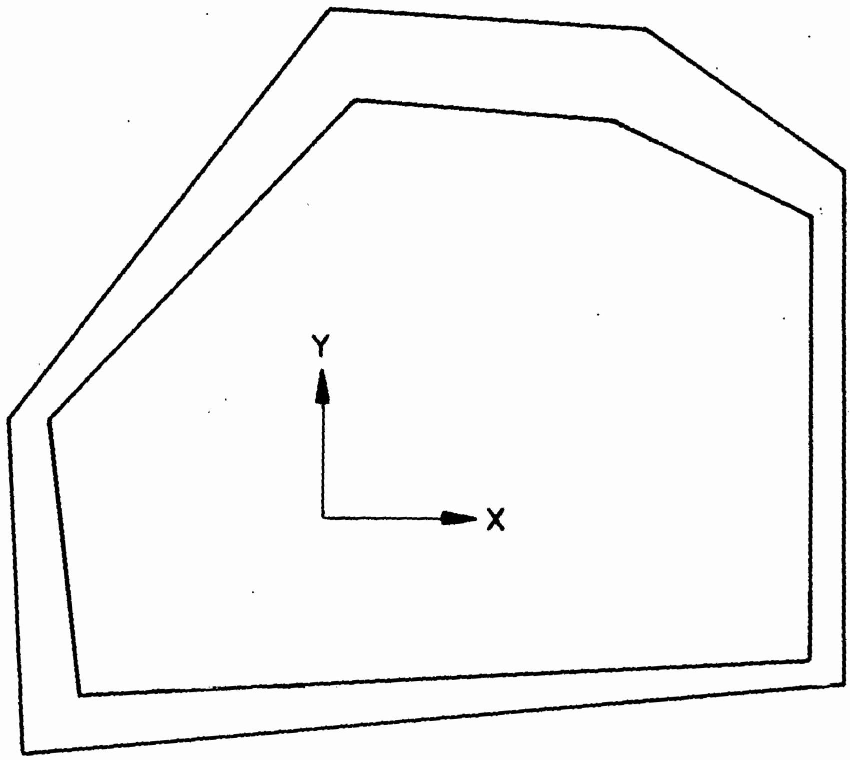


FIGURE C.2 EXAMPLE OF CROSS-SECTION OF TUBE WITH IRREGULAR POLYGON MID-SURFACE

For the remaining cards, Figure C.3 should be consulted.

12111, X1, Y1, X2, Y2, ..., XLAST, YLAST (REQUIRED, IF INDGEM = 21)

The entries on this card (real) define the X, Y - coordinates of the corner points of the sides of the polygon. The corner points are specified in the order indicated in Figure C.3. The sides of the polygon are thus specified in the order indicated in Figure C.3.

12121, NC1, NC2, ... (REQUIRED, IF INDGEM = 21)

The entries on this card (integer) define the number of circumferential subdivisions to be made of each side of the polygon. In the case of Figure C.3, this card would be:

12121, 2, 3, 1

where the dashed lines in Figure C.3 indicate the circumferential subdivisions into elements. The parameters NC1, NC2, ... must add up to NCIRCM on card 10000 (Section 3.1.3).

The circumferential subdivisions are obtained by connecting the points which divide the appropriate edges into equal parts. Thus, in Figure C.3, the dashed line in side 1 of the polygon connects the point which divides edge 1-3 into two equal parts to the point which divides edge 2-4 into two equal parts. In the case of side 2 of the polygon, the points which divide edge 3-5 into three equal parts are connected to the corresponding points which divide edge 2-6 into three equal parts. In this way, side 1 of the polygon will be divided into two elements, side 2 into three elements, and side 3 into one element in the circumferential direction.

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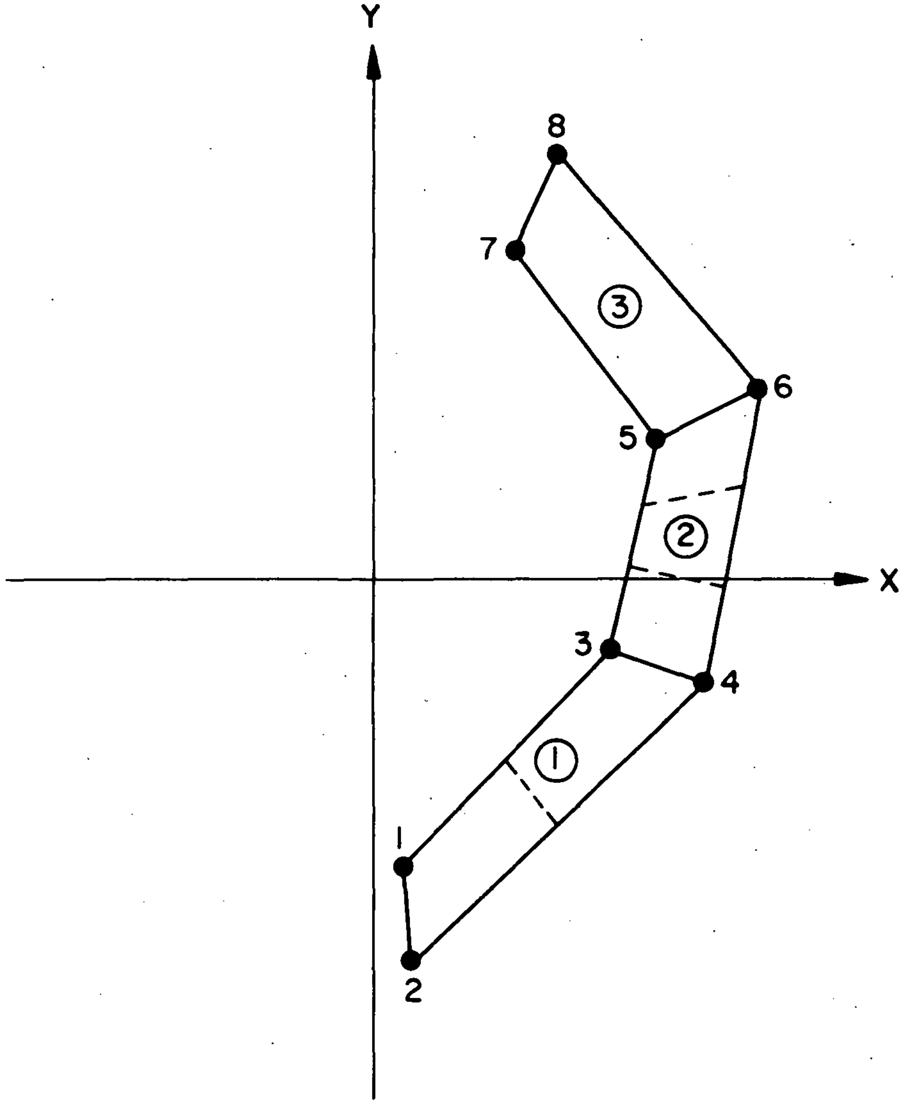

FIGURE C.3 EXAMPLE OF THE DEFINITION OF A CROSS-SECTION WHICH IS AN IRREGULAR POLYGON