E 4/5*

NONLINEAR DYNAMIC RESPONSE OF FAST-REACTOR CORE SUBASSEMBLIES UNDER IMPULSIVE LOADING

T. BELYTSCHKO

College of Engineering, University of Illinois at Chicago Circle, Chicago, Illinois 60680, U.S.A.

J.M. KENNEDY, A. MARCHERTAS

Engineering Mechanics Section, Reactor Analysis and Safety Division,
Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

SUMMARY

Predicting the behavior of the hexagonal fuel assembly duct when subjected to internally generated pressures is a consideration in the safety analysis of the LMFBR. The analysis is complicated by many factors: the three-dimensional effects that arise because of the lack of axisymmetry, the interaction of the duct with the coolant and adjacent ducts, the need to treat nonlinearities of both material and geometric character, the difficulties of obtaining material properties, and uncertainties in the loading. Therefore, this research program has focused on isolating the relative importance of each of these features with the simplest available models.

To a large extent, studies have been possible with two-dimensional models of the hexcan. In these problems, the loadings must be restricted to line loads of sufficient length so that axial effects can be neglected. The finite-element models range from a single hexcan to models which include both the loaded hexcan, two adjacent rows of hexcans, the coolant layers between hexcans, and the fuel-rod assemblies. A nonlinear, transient finite-element program called STRAW is used for the analyses. The program accounts for both geometric and material nonlinearities, and has special features for treating the coolant layer between hexcans by a quasi-Eulerian description so that motions of the coolant can be accurately analyzed. The model has been used with loadings ranging from 20 bars to the kilobar range, and has yielded significant results on damage in adjacent assemblies and the restraining effects of the coolant. For example, preliminary results have shown that deformations of the loaded hexcan are reduced by 25 to 50% when the role of the coolant is included and that corner ductility has very large effects on hexcan response.

The second group of studies is concerned with three-dimensional analyses of the subassembly. These studies are being carried out with a dynamic finite-element program developed at Argonne National Laboratory called SADCAT. This program also includes both material and geometric nonlinearities, and Eulerian procedures for modeling the coolant layer are under development. Though the computer program is very fast, the large number of degrees of freedom associated with these problems has restricted analysis capability at most to a single hexcan and the adjacent wall of the next hexcans. Presently these studies are primarily aimed at establishing the relationship between the results of two-dimensional studies and the complete response. Hence, these studies should shed some light on the widespread belief that the two-dimensional analyses are conservative.

In conjunction with these analytic studies, an experimental program is under way. The first studies will be concerned with line loads in isolated hexcans and hexcans enclosed in fluid environments with known material properties so that the analytic capabilities previously described can be checked. Subsequent experiments will be devoted to establishing gross constitutive properties of the fuel bundle, particularly the effects of the enclosed coolant. Hence, it is anticipated that some experimental comparisons will be available at the time of the 2nd SMiRT Conference.

1. Introduction

In the current U.S. design, the fuel in the liquid metal fast breeder reactor (LMFBR) is stored in stainless steel tubes 1/4 in. in diameter with helical wire wraps about the outside surface. These fuel pins are then packed in groups of 217 in hexagonal cylinders, often called wrappers, subassemblies, or hexcans. The subassemblies are stacked vertically with 0.14 in. gaps between adjacent assemblies. These gaps and the voids between fuel pins created by the helical wires serve as a path for the sodium coolant, which flows vertically through the fuel assembly. A cross-sectional view of an assembly is given in Fig. 1.

The hexagonal wrappers serve several design functions: they provide a means for packing and supporting the fuel pins; they provide paths for the sodium coolant; and they serve as a means of confining accidents within a fuel subassembly. The nature and origin of fuel subassembly accidents is still a matter of considerable debate. Currently, two types of accidents are the focus of most attention:

1) molten fuel-coolant interactions (MFCI) which result in a high pressure acoustic pulse;

2) release of fission gas due to either simultaneous or sequential failure of fuel pins.

An excellent review of these accidents has been given by Rees [1]. Rees and investigators at ANL indicate that at this time it is not clear whether these accidents are credible, what the time scales and peak pressures are likely to be, or whether these postulated accidents constitute the only means of failure. For example, some ANL analysis [2] indicates that if a fragmentation and mixing time is included in the interaction between molten fuel and coolant subsequent to failure of the pin, a considerable decrease can be realized in the heat transfer rate and in the energy of the acoustic wave. These uncertainties have made it mandatory that techniques be developed for predicting the response of the fuel subassemblies for a wide range of pressure loadings and time scales, and for predicting the response of adjacent subassemblies in the case of failure in the accident subassembly.

The goal of this program is the development of a model of an accident subassembly and adjacent subassemblies that is as complete as feasible with current analysis capabilities. By completeness, the authors here refer to inclusion of the various physical phenomena that determine the response in a typical accident: interaction between the accident and adjacent hexcans, vertical flow of the coolant, transient phenomena, and material and geometric nonlinearities. Heat conduction and the mechanism of the accident are not included; it is expected that programs in these particular aspects of the accident problem will provide the data in terms of pressure distributions in space and time.

Models of this type differ from design models in that the primary motivation is not the simplification of the problem to the point where working formulas and design charts can be developed. Instead, the aim is the development of a computer model which can be used to explore hypothetical accidents within a large range of pressure-time histories and spatial distributions, and which includes enough of the key features of the physical system so that these predictions may serve as a reliable indication of expected response. The model thus shares its basic philosophy with REXCO [3], a program developed by ANL for the study of reactor energy excursions. This program has proved invaluable in investigating various types of energy excursions and evaluating containment, such as reactor covers and other energy absorption devices.

The validity of a safety analysis computer code of this type is, of course, highly dependent on the extent of experimental corroboration. Though components of the program can be verified by comparison with closed form analytical solutions and experimental results available in the literature, the validity of the model depends to a large extent on how effectively the key physical phenomena have been chosen and treated. Thus, the certification of a safety evaluation computer code requires that experimental data be obtained for configurations that closely resemble the systems to be evaluated. Without experimental corroboration on the behavior of the entire system, there is a significant possibility of developing a computer model which is quite unreliable because of the omission of specific physical aspects of the problem. For these reasons, an experimental program has been prepared to validate the subassembly accident code. This program will begin in July, 1973 and will be briefly described in this paper.

2. Method of Analysis

Whereas REXCO was developed on the basis of a Lagrangian finite difference scheme, it was decided early in the development of the subassembly-to-subassembly failure code that a finite element procedure would be more appropriate. The main reasons for this is the greater versatility inherent in the finite element procedure, specifically the ease with which irregular geometries and inhomogeneities can be treated by the finite element method. An additional benefit that was discovered later in the course of the program is that the finite element method lends itself easily to multiple descriptions within one code; i.e., it permits the use of Lagrangian and Eulerian descriptions within one mesh. This has become particularly useful in modeling the thin layer of coolant that separates adjacent hexcans.

The computer code developed for this program is STRAW (Structural Transient Response of Assembly Wrappers). This is a special purpose version of WHAM (Waves in Hysteretic Arbitrary Media). These computer codes are two-dimensional, dynamic transient codes with both flexural (beam) and continuum elements. Both codes employ lumped masses and explicit temporal integration and have provisions for artificial viscosity. Material nonlinearities, such as elasto-plastic behavior, and geometrical nonlinearities caused by large rotations are included. Because of the two-dimensionality of the code, the analyses are restricted to line loads of sufficient length so that a plane strain analysis of a horizontal cross-section of the fuel assembly is appropriate. Another code is now under development which includes plate and three-dimensional continuum elements.

The principal feature of these codes is the use of convected coordinates, which are coordinates that rotate and translate with the element. Convected coordinates were first used in finite elements by Argyris, Kelsey and Kamel [5] in static analysis; the first application to dynamic analysis is by Belytschko and Hsieh [6], [7], who developed a total rather than the incremental convected coordinate procedure used by Argyris; the total formulation may be more suitable for transient problems, for it eliminates one source of truncation error.

In the convected coordinate procedure, each element is associated with its own coordinate system which follows its rigid body motion. For problems with small strains but large rotations, which incidently, encompasses a large class of nonlinear engineering problems, it can be shown that the strains in the convected coordinates are linearly related to what are termed "deformation" displacements. The latter correspond to the difference between total displacements and rigid body displacements, which may also be viewed as simply the displacements of the element relative to the convected coordinates. Consequently, within the convected coordinates, the relationship between element nodal forces and stresses involves only linear functions of the displacement shape functions. The important nonlinearities due to the large rotations are treated completely by transformations between the convected and global coordinates. Thus, the computation of nodal forces is considerably simplified. This is of particular importance in flexural elements, such as beams and plates, for in nonlinear material problems, numerical quadrature through the thickness is required. By simplifying the relationships used in these computations, significant economies can be achieved in the code running times. A complete description of these procedures can be found in [Refs. 6 and 7].

For purposes of modeling the coolant layer between hexcan wrappers, a special quasi-Eulerian description has been developed. The motivation for this type of description is that the thinness of this coolant layer requires that at most one layer of elements be used. Otherwise, the elements would be so thin that extremely small time steps would be needed to maintain numerical stability. However, the use of a single element through the thickness does preclude the imposition of the viscous zero slip condition at the interfaces. Therefore, a sliding interface is used between the hexcan walls and coolant which permits unequal tangential velocities for the coolant and wall. Viscosity is modeled in an approximate manner by imposing equal and opposite tangential forces to the hexcan walls and coolant which are proportional to the relative tangential velocities. A complete solution of the coolant flow would, of course, be so complex that its incorporation into the complete subassembly code is not feasible; so this single layer, sliding interface model is quite attractive.

The coolant elements are treated by a quasi-Eulerian mesh which consists of cells which move with the enclosing hexcan walls, as shown in Figs. 2a and 2b. So, while each cell moves with time, it does not move with the material it encloses. Therefore, it is neither a Lagrangian nor an Eulerian mesh. Within each cell, the velocity is described by shape functions with linear variations on the element sides. The component of the fluid velocity normal to the adjacent wall is constrained to move with the wall, while the tangential velocity is unconstrained. Equations of continuity are imposed in each element and momentum-force balance are expressed at each node as functions of the nodal velocities and element density. Lumped masses represent the inertial properties, and since the total mass within each cell varies with time, the lumped masses also vary with time.

This type of description is essential if the coolant layer is to be modeled by a single row of elements with sliding interfaces between it and the hexcans. If a Lagrangian description were used to model the fluid, the flow of the fluid would result in separation of adjacent fluid-wall nodes, as shown in Fig. 2c. Secondly, Lagrangian schemes with sliding interfaces are not suitable for flow about concave corners; the difficulties are illustrated in Fig. 2d. Strictly Eulerian schemes also present difficulties, as shown in Fig. 2e; the movements of the walls through the Eulerian mesh would require several layers of coolant elements and complicated procedures for treating subdivided elements.

3. Material Properties

One of the major difficulties in the development of a reliable model for subassembly-to-subassembly failure propagation lies in the constitutive characterization of the materials, the hexcan walls and the fuel bundle-coolant composite. Sources of difficulties are the uncertainties in the probable temperatures during an accident and the degree of irradiation of the hexcan walls. Moreover, because helical wire wrappers separate the fuel bundles, frictional and crushing behavior, which are difficult to treat mathematically, are predominant.

The steel is modeled as an elastic-plastic material with linear, isotropic strain-hardening. Data has been obtained for the behavior of the stainless steel used in the manufacture of the hexcan walls for various degrees of irradiation [8]. The uniaxial stress-strain curve at 1000°F for neutron fluences of $2 \times 10^{23} n/cm^2$ are given in Fig. 3. The latter figure is an extrapolated value based on lower values of irradiation and represents the end of life of the material. The ductility of the steel varies from 5.6% strain at failure before irradiation to 1.06% strain at end of life at 1000°F. Data for strain rate effects is not yet available.

The steel is nominally 20% cold worked, and the yield value given in Fig. 3 is based on this degree of cold working. However, J. E. Ash [9] has reported a study of experimental results for the EBR-II and STRAW computations which indicate that the degree of coldworking often increases in the corners of the hexcans and that this has a substantial (10 to 50%) effect on the response if the yield-point is exceeded.

The fuel cells and coolant within the hexcans are idealized as a two-phase homogeneous material. The effective stresses corresponding to fuel bundle response and the pressure in the sodium are combined to obtain the total stresses in a manner analogous to the computation of the stresses in saturated soils. The computation of the pressure in the sodium is straightforward. On the other hand, the development of appropriate formulae for predicting the effective stress due to the fuel bundles is an extremely challenging problem which probably cannot be surmounted without an extensive experimental program.

Several alternative forms of constitutive laws are under consideration. The most promising appears to be a modified form of the Coulomb flow law, such as that given by Sandler and diMaggio [10]. In this type of flow law, the yield surface consists of a Coulomb surface with a cap so that only finite pressures can be obtained before the initiation of plastic flow; these constitutive equations thus differ from the Coulomb law in that beyond certain pressures, the strains are not reversible. However, just as in the Coulomb law, the effective shear (or to be more precise, the second invariant of the deviatoric stresses) is limited to a fraction of the pressure, which is essentially the coefficient of friction of the material. Thus, this type of constitutive equation is based on frictional behavior under shear stresses, and irreversible response, such as crushing, for pressures beyond a yield point. This matches the behavior expected in the fuel bundles; when subjected to shearing stresses, the resistance of the fuel bundle results primarily from frictional forces between adjacent fuel pins, and the maximum shear depends on the pressure; when subjected to pressures beyond a certain point, the helical wire wrappers crush and irreversible deformations result.

The parameters which must be determined experimentally to define a material by this constitutive equation are the coefficients of friction, the elastic constants of the system, and the shape of the pressure-dilatation curve in the irreversible strain domain. This experimental program has not yet begun so an elastic law with constants based on the Mark II [11] tests are currently used.

An additional factor which must be considered in two-dimensional cross-sectional models of the subassemblies is the transverse flow of the coolant. Results which will be cited in the next section show that neglecting this transverse flow can result in extreme overestimation of the strength of adjacent subassemblies, particularly in long duration loadings. The transverse flow is included in this model by accounting for the transverse mass flux before computing the dilatation. In computing the transverse flux, the transverse velocity is computed by using a one degree of freedom system which accounts for the inertia and viscous resistance of the slug of coolant above the accident level. Acoustic effects are included in an approximate manner by setting the length of the slug equal to ct (c = acoustic wave speed, t = time) until the acoustic wave reaches the end of the hexcan.

4. Preliminary Computer Code Results

Preliminary code computations have been undertaken with the aim of verifying the code by comparison with published experimental results and of assessing the role of some of the physical aspects of the problem, such as interaction of the accident assembly with its surroundings and transverse; i.e., vertical flow of the coolant. The comparison with published experimental results has been described in Refs. [4, 6 and 7], and will not be described any further herein.

In studying some of the physical aspects of the problem temporally, triangular pressure pulses with peaks of 1000 to 15,000 psi, rise times of 100 μsec to 1000 μsec and decay times of 500 μsec to 3000 μsec have been utilized. The currently postulated nominal local MFCI is approximately a triangular pulse with a rise time of 1 msec, decay of 3 msec and peak of 1170 psi. The fundamental frequency of an isolated hexcan is about 0.3 msec, so that for this postulated MFCI, the response is essentially quasi-static for an isolated hexcan. For this reason and because of the cost of studying such long-time histories in exploratory work, shorter pressure histories have been used.

The first set of results reported here compare the response of an isolated hexcan with the response of the hexcan when the adjacent hexcan and channel sodium are included, as shown in Fig. 4. An isolated model here refers to a single, loaded hexcan which is completely unrestrained. Only a one-twelfth section of the hexcan is needed because of symmetry. The assembly at the left of Fig. 4 is the accident assembly and the acoustic pulse is applied directly to the wall of this hexcan. The right-hand assembly has a sliding constraint at the upper right-hand corner, while the fluid motion at that edge is constrained by an applied pressure proportional to the square root of the velocity. The fuel pins and sodium coolant within the assembly and the vertical flow were omitted in this model. The hexcan walls are represented by flexural elements and the continua by linear displacement or velocity triangular elements; all are in a state of plane strain, as described in Ref. [4].

The maximum displacements for all of the loadings occurred at the midpoint of the accident hexcan flat, point A in Fig. 4. Figure 5 shows the displacement histories for two of the load cases and compares them with the displacement histories of an isolated hexcan. Figure 6 makes a similar comparison of the strain history at the point of maximum tensile strain, which is the inside corner, point B in Fig. 4. A complete comparison of maximum displacements and strains is given in Table I. For these pressures, failures would be expected in most of these hexcans, since the ductility limits are exceeded in the corner.

It can be seen from the results that the inclusion of the adjacent hexcan in the model results in a 30% to 50% reduction in the maximum displacement and a somewhat smaller reduction in the maximum strain. What appears to happen, in effect, is that particularly for the more impulsive loadings, little horizontal flow of the sodium takes place and the adjacent hexcan flat deforms almost to the same extent as the loaded one. Hence, the presence of the fluid permits a large portion of the impulsive energy to be absorbed by the adjacent hexcan.

In fact, if one takes the average displacement; i.e., the residual displacement, as a measure of the plastic energy absorption, the isolated hexcan absorbs almost twice as much energy in all cases. For example, for loading 3, the residual displacements are 0.13 in. and 0.065 in. for the isolated and enclosed hexcans, respectively. This particular partitioning of the impulsive energy is, of course, highly dependent on the extent of fluid coupling. This particular model overestimates fluid coupling because of neglect of vertical flow. However, some recent results show that for rise times of less than 400 μsec, even when vertical flow is permitted, the coupling is very strong.

Other interesting aspects of these results are that (1) the period of the hexcan decreases markedly after deformation because of the arching and (2) the fundamental period of the enclosed hexcans is increased dramatically. These observations can easily be noted in Fig. 5. The latter is of course expected since the sodium layer adds mass but no flexural resistance to the two beam-sodium layer composite.

Figure 7 shows a more complete model of the cross-section which includes the entire adjacent hexcan and its contents. This model has been used primarily for studying the effect of vertical flow of the coolant. Figures 8 and 9 show displacement and strain histories with and without vertical flow for a very short loading, and in addition, show the response of an isolated hexcan to the same loading. The effects of vertical flow are seen to be quite significant. However, though the inclusion of vertical flow softens the system, its effect is mainly seen in the volume loss within the adjacent hexcan, not in the coolant layer. The deformations of the adjacent hexcan flats are still predicted to be almost equal.

These results demonstrate the importance of including the adjacent hexcans in predictions of hexcan response. The surroundings reduce the period of the loaded hexcan and serve as an energy sink. Though the sodium is comparatively soft and the impedance mismatch between the sodium and hexcans is great, the thinness of the sodium layer results in strong coupling of the response of the adjacent hexcan walls. Thus, the hexcan response problem bears a strong resemblance to structure-media interaction problems found in civil engineering where the inclusion of the surrounding media in the model is essential for reliable predictions of response.

As an example of another type of accident possibility, Figs. 10, 11 and 12 show the model and response for a hexcan loaded externally. The loading here corresponds to an MFCI in an adjacent hexcan which ruptures the hexcan; the response of the subject hexcan prior to rupture of its neighbor is neglected. The displacement and strain histories, Figs. 11 and 12, respectively, are given for both an empty and filled hexcan.

5. Experimental Program

Possibly the most extensive effort to date in evaluating subassembly-to-subassembly failure propagation has been conducted in the United Kingdom. A recent review of this program by Rees [1] indicates that rather elaborate and costly experiments have been performed for the PFR and that plans are well underway for similar experiments with the SNR core. These full scale experiments have been carried out in a water environment. Mild steel has been used to simulate stainless-steel properties at operating temperatures, though apparently no attempt has been made to duplicate radiation embrittlement effects. Extensive instrumentation was included in the hope that an analysis eventually will become available.

In the United States the experimental effort has been comparatively meager. Although some industrial experimental work on subassembly damage propagation has been performed, none of this work has evidently been published. Some experimental studies have been carried out at ANL and other laboratories. Koenig [11] has tested the response of the EBR-II hexagonal can to a simulated fission gas release from a single fuel pin. The main objective of these experiments was the determination of whether this type of accident would cause sufficient damage to preclude removal of the accident subassembly. In addition, a pressure source to simulate fission gas release has been developed [12] and preliminary studies of the internal resistance of FFTF subassmelbies have been made [13]. The scope of the latter studies was, however, extremely limited. Only across the flats compressive loading of cold subassemblies was studied, and because of the absence of shear load results, even rudimentary constitutive characterizations of these innards are still impossible.

The experiments in this program will be carried out in steps of increasing complexity in conjunction with the analytical program, so that each component of the computer code can be adequately tested. This approach was chosen because if a complex analysis were undertaken directly on prototype experiments, it is likely that either the source of discrepancies could not be isolated or compensatory errors would be introduced in matching the experiments that would render the code worthless for accidents of a different character.

The initial tests will be performed with single loaded wrappers, both empty and with fuel pins, isolated in an environment of air or water. The objectives of this phase are the development of a suitable pressure source and the determination of material properties and their effects on response. The determination and verification of a line pressure source will be performed with cylindrical wrappers so that REXCO, an axisymmetric energy excursion code, can be used for source verification. The internal pressure in an assembly filled with liquid is a function of volume so that the actual load at any instant of time is very sensitive to this parameter. To eliminate this difficult effect, detonation gases will be used for generation of the pressure pulse. In addition, since shock loading is not anticipated in an MFCI, and since shocks introduce additional analytical difficulties, efforts will be made to develop a shock-free energy source. As for material properties, emphasis is currently contemplated for two areas: (1) the effects of ductility, coldworking, and irradiation on hexcan response and (2) the constitutive characterization of the fuel-pin coolant composite as a homogeneous, orthotropic material (isotropic in a two-dimensional cross-section). For purposes of isolating the effects of ductility, tests will be performed initially on fully annealed hexcans and then compared with prototypical hexcans where variations in extent of coldworking are expected. The first phase of the experimental program, which may be designated as the simple tests, will conclude with the following: (1) internal blast loads on single prototypical hexcans in air and water, and (2) external blast loads (if feasible) on a single subassembly can with and without fuel pins. The end effects in all these simple tests will be minimized by using line loads, long cans, and simple supports.

The purpose of the second phase of the experimental program, which may be called the complex model tests, is the study of subassembly-to-subassembly failure propagation within clustered hexcans. Whereas the first phase will treat systems sufficiently defined so that discrepancies between computer code predictions and experimental results can be ferreted out, the complex model tests include additional complicating features: the channels between subassemblies, and the fuel pins. The complex tests will include: (1) clustered empty hexcans in water and (2) clustered hexcans with simulated and prototypical internals immersed in water.

These last tests, in combination with the simple tests, will represent a crucial corroboration of the computer code. By adding essentially one complicating feature at a time, it is reasonable to assume that any final agreement between codes and experiments is indicative of an accurate representation of the key physical phenomena. Thus, upon completion of the program, the code should be suitable for analysis of a wide variety of hypothetical accidents. Although this procedure in the development of a code is admittedly quite time-consuming and costly, it appears to be the only way in which a reliable code can be obtained for such complex systems.

Acknowledgements

The authors would like to gratefully acknowledge their helpful discussions with T. J. Marciniak.

This work was performed in the Mechanics Section of the Reactor Analysis and Safety Division, Argonne National Laboratory, U.S.A., and it was supported by the U. S. Atomic Energy Commission.

References

[1] REES, N. J. M., "Mechanical Effects of Core Accidents," Intl. Conf. on Eng. of Fast Reactors, Karlsruhe, Germany (1972).

[2] CHO, D. H., CHEN, W. L., and WRIGHT, R. W., "Pressure Pulses and Mechanical Work from Molten Fuel-coolant Interactions: A Parametric Study," Trans. Am. Nucl. Soc., Vol. 14, p. 290 (1971).

[3] CHANG, Y. W. and GVILDYS, J., "Dynamic Response of Reactor Containment to High-Energy Excursion," 1st Intl. Conf. on Struct. Mech. in Reactor Tech., Vol. 2, E2/4 (1971).

[4] BELYTSCHKO, T., KENNEDY, J. M. and HSIEH, B. J., "Convected Coordinates for Transient Nonlinear Finite Element Analysis," 2nd Intl. Conf. on Struct. Mech. in Reactor Tech (1973).

[5] ARGYRIS, J. H., KELSEY, S. and KAMEL, H., "Matrix Methods of Structural Analysis: A Precis of Recent Developments," Matrix Methods of Structural Analysis, deVeubeke (ed.), AGARDograph 72, Pergamon Press (1964).

[6] BELYTSCHKO, T., and HSIEH, B. J., Nonlinear Transient Finite Element Analysis with Convected Coordinates," to be published Intl. J. of Num. Methods in Eng.(1973).

[7] BELYTSCHKO, T. and HSIEH, B. J., "Nonlinear Transient Analysis of Shells and Solids of Revolution by Convected Elements," AIAA/ASME/SAE 14th Structures, Structural Dynamics, and Materials Conf., Williamsburg, Va., Mar. 20-22, 1973.

[8] BRIZES, W. F., "Stress Strain Relationship for CW 316SS," FMT-FI-WFB-5, (Oct., 1972).

[9] ASH, J. E., Personal Communication, March 6, 1973.

[10] DIMAGGIO, F. L., and SANDLER, I. S., "Material Model for Granular Soils," J. Eng. Mech., Div. ASCE, Vol. 97, pp. 935-949 (June, 1971).

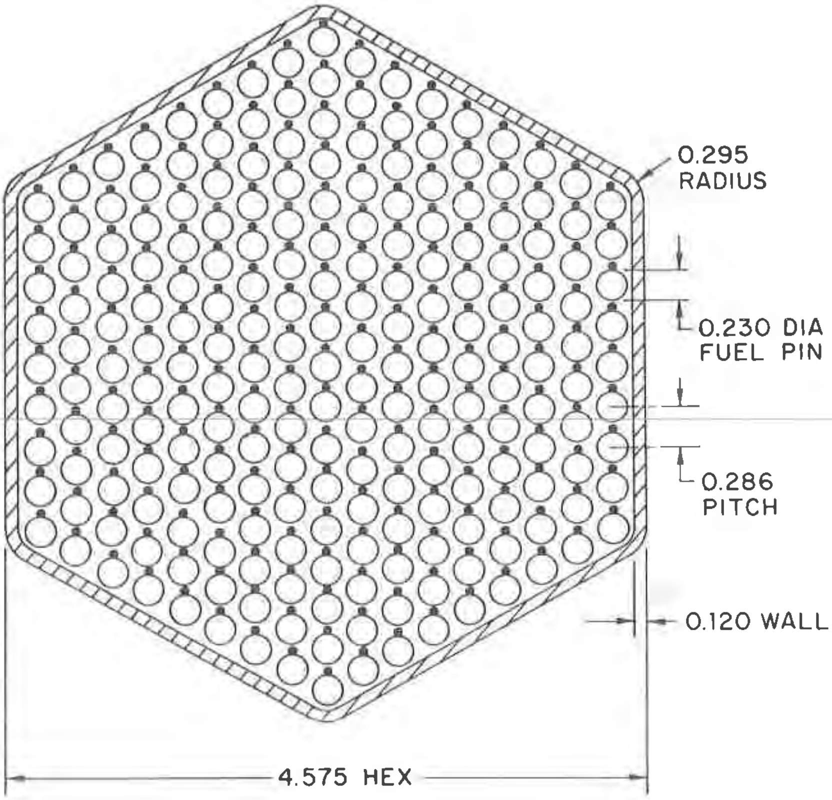
[11] KOENIG, J. F., "Reactor Development Progress Report," ANL-7765, pp. 41-47, (Dec., 1970).

[12] KOENIG, J. F., "Reactor Development Progress Report," ANL-RDP-6, pp. 1-24 (June, 1972).

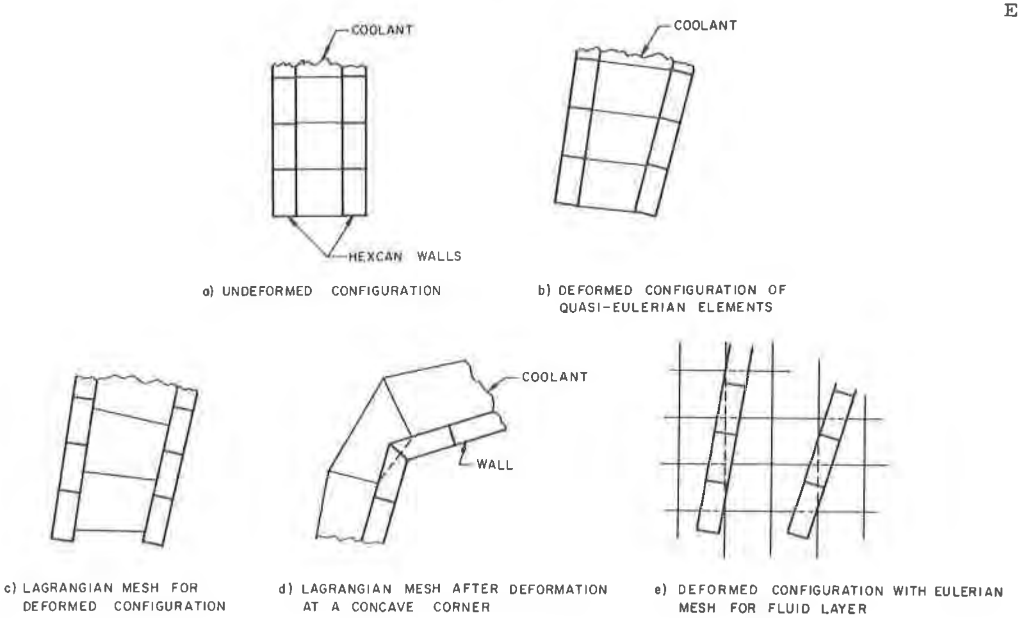
[13] BAKER, K. B. and BLAHNIK, D. E., "CCTL Mark-I and Mark-II Prototypic FFTF Subassembly Compression Test Development Work," WHAN-FR-18 (Aug., 1970).

Table I
Maximum Displacements and Strains
for Various Loadings

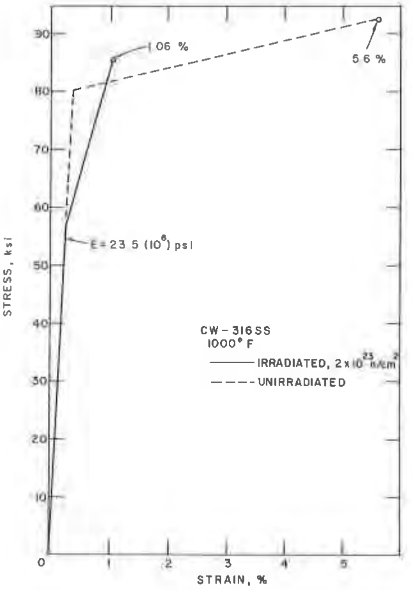
	Loading 1	Loading 2	Loading 3	Loading 4
Max. Disp. of Pt. A-Fig. 4	.0850 in.	.1070 in.	.0920 in.	.0713 in.
Max. Disp. of Pt. A-Isolated Hexcan	.1603 in.	.1815 in.	.1570 in.	.1213 in.
Time-to-Max. Disp. Pt. A, Fig. 4	.218 msec.	.244 msec.	.338 msec.	.516 msec.
Time-to-Max. Disp. Pt. A-Isolated Hexcan	.196 msec.	.204 msec.	.294 msec.	.460 msec.
Max. Strain at Pt. B-Fig. 4	4.61%	5.78%	5.05%	4.02%
Max. Strain at Pt. B-Isolated Hexcan	7.21%	8.47%	7.20%	5.69%



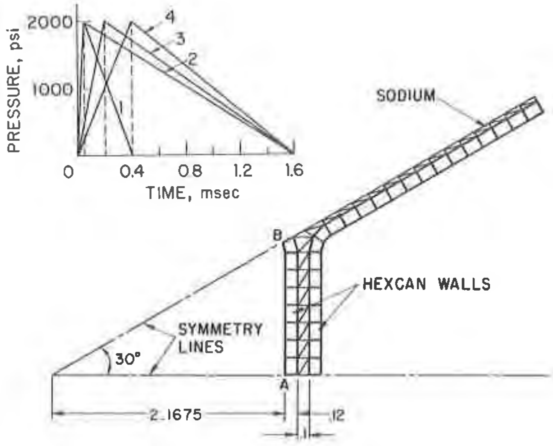
(1) Cross-section of Fuel Subassembly.



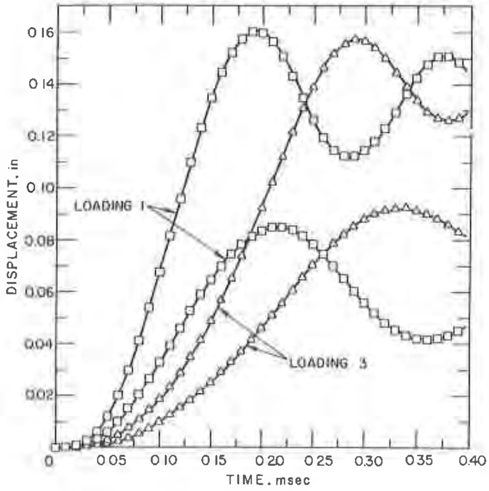
(2) Quasi-Eulerian Fluid Elements for Coolant between Hexcans.



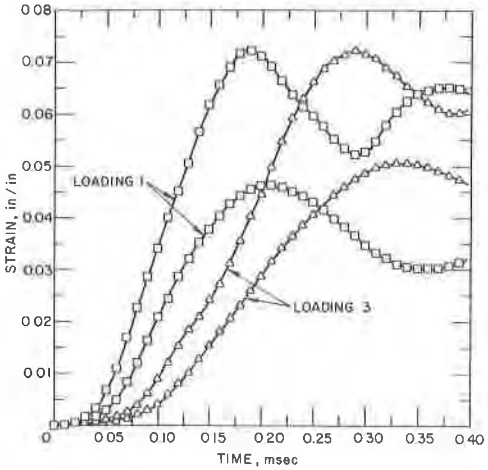
(3) Stress-strain Curve for CW-316SS at 1000°F.



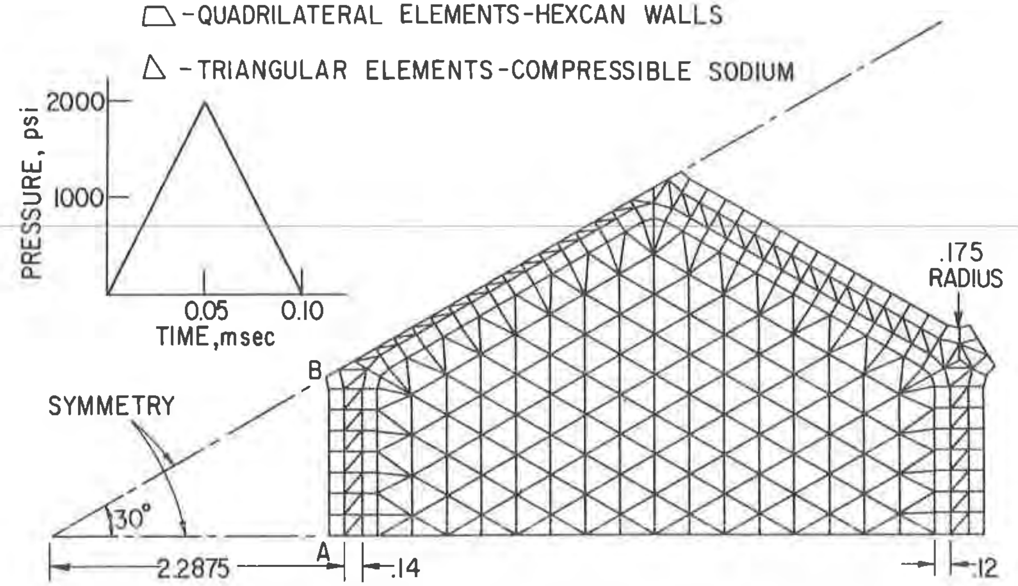
(4) Finite Element Model for Fluid Coupling Study and Pressure-time Loadings.



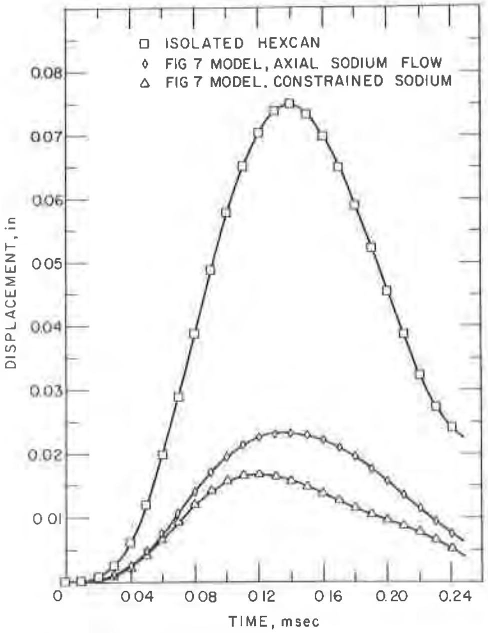
(5) Displacements at Midpoint of Pressure Loaded Hexcan Flat (Point A of Fig. 4).



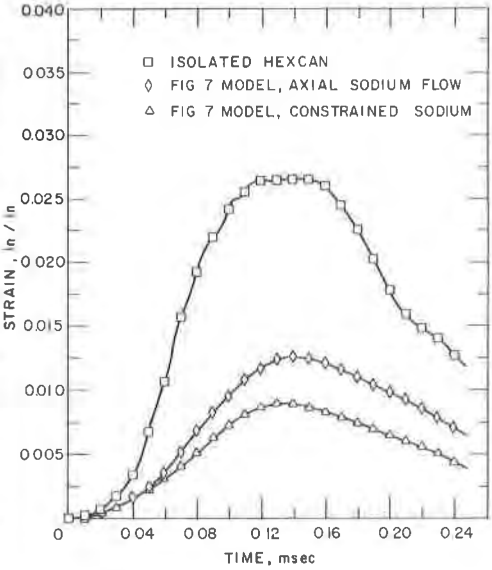
(6) Strains at Inside of Corner of Pressure Loaded Hexcan Corner (Point B of Fig. 4).



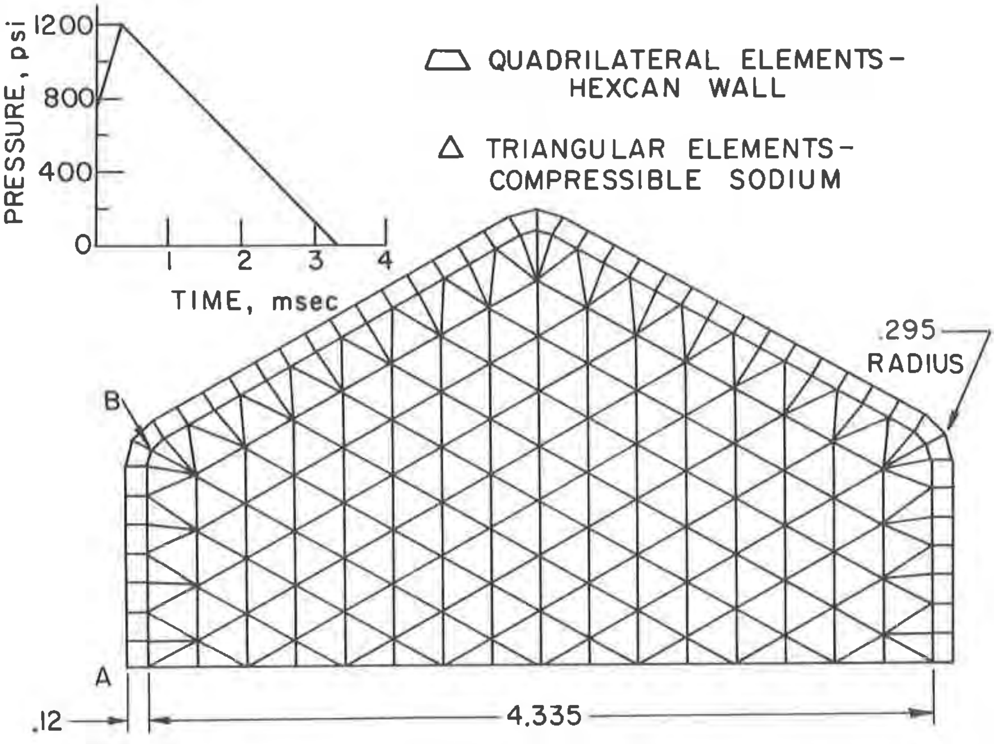
(7) Finite Element Model for Vertical Flow Study and Pressure-time Loading.



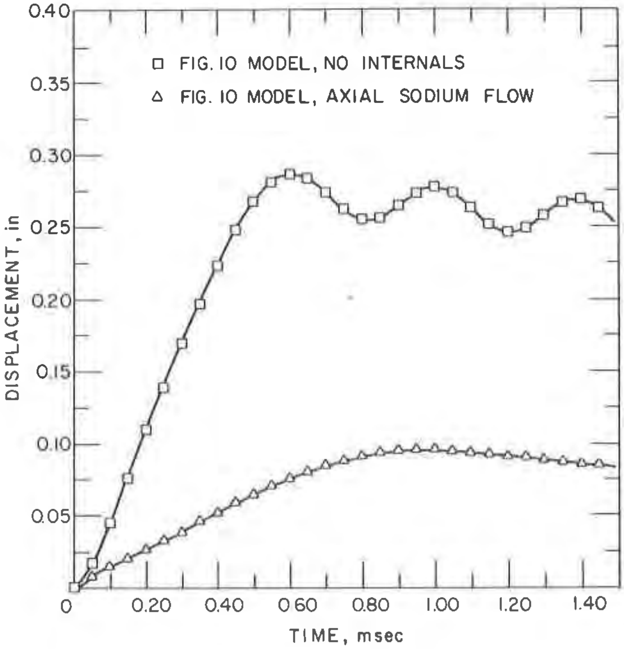
(8) Displacements at Midpoint of Pressure Loaded Hexcan Flat (Point A of Fig. 7).



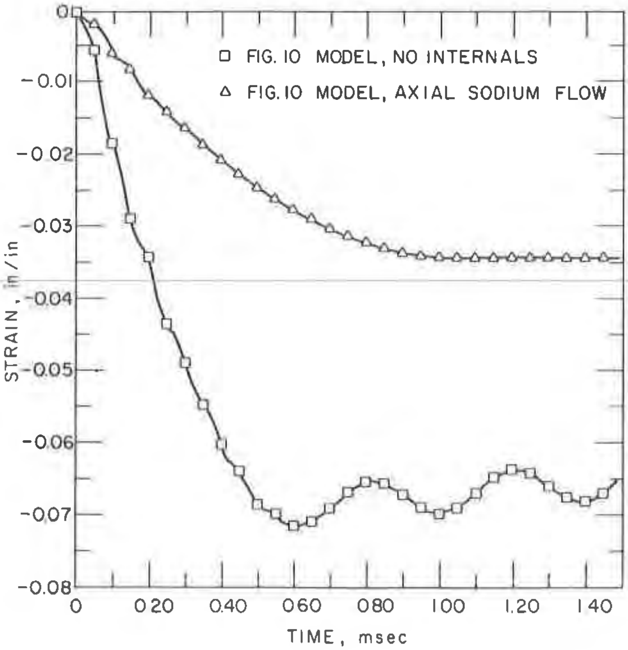
(9) Strains at Inside of Corner of Pressure Loaded Hexcan Corner (Point B of Fig. 7).



(10) Finite Element Model for External Loading Study and Pressure-time Loading.



(11) Displacements at Midpoint of Pressure Loaded Hexcan Flat (Point A of Fig. 10).



(12) Strains at Inside of Corner of Pressure Loaded Hexcan Corner (Point B of Fig. 10).