RESPONSE OF SUBASSEMBLY MODEL WITH INTERNALS

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SUMMARY

In safety analysis at the subassembly level, the following aspects of subassembly response are of concern:

(1) the structural integrity of the subassembly within which the accident occurs;
(2) the structural integrity of adjacent subassemblies, particularly the maintenance of sufficient cross sectional area for flow of the coolant; and
(3) prevention of damage to fuel pins in the adjacent subassembly, for this could lead to additional energy release and thus the propagation of the accident.

For the purpose of predicting the structural response in such accident environments, a program STRAW has been developed. This is a finite element program which can treat the structure-fluid system consisting of the coolant and the subassembly walls. Both material nonlinearities due to elastic-plastic response and geometric nonlinearities due to large displacements can be treated. The energy source can be represented either by a pressure-time history or an equation of state.

Because of the lack of any simplifying symmetry in the geometry of the subassembly the program uses a quasi-three dimensional model. The cross section of the accident hexcan and the adjacent hexcan are modelled by a two-dimensional finite element mesh which represents the hexcan walls bv flexural element and the internals by two-dimensional continuum elements. This mesh is coupled to a series of one-dimensional elements which represent the axial flow of the coolant and the longitudinal stiffness of the fuel pins and hexcan. The latter is of importance in the adjacent hexcan, for its lateral displacement is resisted entirely by this flexural behavior and its inertia. The adequacy of such quasi-three-dimensional models has been examined by comparing the STRAW results against almost complete three-dimensional analysis performed with the REXCAT program. In this program, the accident hexcan is represented in a truc three-dimensional sense by plate-shell elements, whereas the internals are represented as axisymmetric. These comparisons indicate that the quasi-three-dimensional approach employed in STRAW is valid for a large range of pressure time histories; the fidelity of this model suffers primarily when pressure reaches a peak over a very short time, such as 5-10 microseconds.

The second aspect of subassembly modelling which is particularly difficult is the constitutive representation of the internals for the continuum element. In this paper, a new approach to their constitutive characterization is described. The main characteristic of this model is the representation of the internals by two layers of superimposed elements: (1) a layer of Lagrangian elements which represent the matrix of the fuel pins, and (2) a layer of quasi-Eulerian elements which represent the coolant. The nodes of the quasi-Eulerian elements are constrained to move with the Lagrangian matrix elements, so that any relative velocities represent the motion of the coolant through the fuel pin matrix. This motion is governed by a diffusion type law such as is commonly found in the motion of pore water through soils. The constitutive characterization of the fuel pin matrix has been obtained by treating it as a continuum with substructure. As a framework for characterizing the resultant stress-strain relations, a Coulomb type of elastic-plastic law has been choosen. The coefficients were obtained from finite element analysis of the substructure, experiments, and analytical considerations of the mechanisms of fuel pin-wire wrapper rearrangement.

In the interpretation of the results of the computations, attention has been focused on the partitioning of energy from the source. Thus, in all computations, the energy partitioning between axial flow, deformation of the accident hexcan, adjacent hexcan, and internals has been studied. The results show that for pressure with rise times on the order of 1 msec, most of the energy is imparted to the axial flow. It is only for very rapid sources that a significant amount of energy is imparted to the adjacent subassembly or its internals.

1. Introduction

Safety studies of the internal components of the liquid metal fast breeder reactor (LMFBR) are concerned with the mechanical integrity at three levels: the cladding of fuel pins; the hexagonal subassemblies (often called hexcans) within which the fuel pins are packed; and the primary containment. Among the issues which are of concern in the safety analysis at the subassembly level are the following: (1) the structural integrity of the subassembly within which the accident occurs; (2) the structural integrity of adjacent subassemblies, particularly the maintenance of sufficient cross sectional areas for the flow of the coolant; and (3) damage to the fuel pins in the adjacent subassembly, which could lead to additional energy release and thus the propagation of the accident.

Since the late 1960's efforts have been underway in Great Britain, West Germany and the United States to determine the capacity of subassemblies to withstand energy releases resulting from an accident. The British efforts [1,2] have been primarily experimental; full-size models of 19 and 61 subassembly clusters have been subjected to high explosive charges detonated in a central subassembly. Charges which yielded peak pressures of 100 MPa with rise times of 5 msec and durations up to 50 msec were used. The experiments showed tremendous distortions of the adjacent subassemblies, but the subassemblies two or more rows removed from the accident suffered little change in cross-sectional area. Since these pressures are far larger than those associated with any thermodynamical process that has been envisioned, it is clear that attention in subassembly failure propagation analysis can be confined to the one or two rows of subassemblies adjacent to the accident.

The work in West Germany has been reported in [3 and 4]. Analytical and experimental efforts have dealt primarily with the role of the fuel bundle in subassembly response and the bending behavior of the adjacent hexcan. The fuel bundle has been represented by a lattice of truss elements with resistance only in compression. Comparisons have been made with quasi-static experiments which show good agreement. Also, some models for channel flow, similar to the approach in COBRA [5], have been developed to account for the coolant.

The studies in the United States also comprise analytical and experimental efforts. The experimental efforts have focused on the response of the isolated hexcan, a hexcan surrounded by coolant and small subassembly clusters [6,7]. Comparisons with analytic results, Ash and Marciniak studies [8,9], show good agreement but have identified several potential difficulties, such as the large effects of corner work-hardening on the response of the hexcan.

The major analytical tools which have been developed for the subassembly studies structural safety at Argonne National Laboratory are the programs STRAW [10,11], SADCAT [12,13] and REXCAT [14]. STRAW is a two dimensional nonlinear finite element program with continuum elements that are used to represent the internals of the subassembly and flexural elements which are used to represent the subassembly walls. The program is used to model cross-sections of the subassembly geometry normal to the axis of the subassemblies and fuel pins. The three dimensional effects, such as the axial flow of the coolant and the axial bending resistance of the adjacent subassemblies, are treated by coupling one dimensional models of the axial flow and the flexural resistance to the two dimensional models. This approach entails assumptions about the phenomenology of the accident, but as a consequence yields significant simplifications and economy of computation. Therefore, configurations involving both the accident hexcan and one to three layers of adjacent hexcans can be treated by STRAW. SADCAT, on the other hand, is a three dimensional plate-shell program which can model the actual geometry of the subassemblies without any geometrical simplifications. In REXCAT, SADCAT is coupled with the two dimensional Lagrangian finite difference program REXCO-HT [15]. Thus the internals of the hexcan, including both the energy source and the hydrodynamics, are modelled as axisymmetric whereas the hexcan walls are treated as three dimensional. The two programs are coupled so that the pressure on the hexcan at any cross-sectional level is uniform and varies only axially. This coupling in effect allows some of the important three dimensional effects in the accident hexcan to be evaluated.

The major analytical efforts which remain are: (1) development of more sophisticated models for the subassembly internals, that is, the fuel pins and coolant, (2) development of models for representing three dimensional effects in subassemblies adjacent to the accident subassembly.

In this paper, the approaches taken to these developments will be described.

2. Three Dimensional Effects

One of the difficult aspects of the subassembly response problem is its inherent three dimensional character. However, because of the inordinate computational expense associated with complete three dimensional analyses, they had to be ruled out and alternate models which capture limited portions of the three dimensionality had to be developed. We will call these models 2D+ and 3D- models. The 2D+ models were constructed by augmenting standard 2D models, while 3D- models were constructed by using the complete 3D representations only over parts of the model, with 2D models in the remainder. These procedures of course entail appropriate couplings between the 2D and 3D portions of the model.

The 2D+ models were generated in the program STRAW. STRAW is a plane, two dimensional, transient finite element program which can model both the hydrodynamics and structural components. Geometric and material nonlinearities are treated.

The characteristics of a STRAW 2D+ model are illustrated in Figure 1. As can be seen from the figure, the area of energy release is expected to be uniform in the z direction, which coincides with the axis of the subassembly. The behavior in this energy release zone is represented by a plane mesh of two dimensional elements. The axial flow is modelled by a set of one dimensional elements which are superimposed on the two dimensional plane mesh, with the axis of the one dimensional flow perpendicular to the plane mesh. The flow is assumed to be symmetric about the midplane of the energy release zone, so that in addition to the upward flow model illustrated in Figure 1, a downward flow of equal velocity is assumed in a lower column. As many plane elements as desired can be superimposed by a single element of the axial flow model; the axial flow is then driven by an area-weighted average of the pressures in the plane elements which are superimposed by the axial flow elements. The axial flow elements are therefore called "superelements". Only vertical flow (in the z direction) is modelled in the superelements; any flow in the x and y direction above and below the energy release zone is neglected.

Although the initial pressure waves propagate through both the solid fuel pins and the sodium, only the motion of the coolant is considered in superelements, for it is assumed that the fuel pins are not completely ruptured, but maintain axial coherence, so that very large motions will not be experienced by the fuel pins. Calculations have shown that the coolant exhibits rather large displacements. For example, when the energy source generates a pressure of about 70 bars for about 4 milliseconds, the coolant moves on the order of 1 cm. Thus it is evident that most of the energy imparted to the axial column is employed in overcoming the inertial and viscous resistance of the fluid; probably very little energy is expended in the accoustic wave that moves through the fuel pins. Therefore, in the axial model, attention is restricted to the fluid; the pins are treated as an inert, incompressible constitutent.

The hexcan walls are treated as strictly two dimensional in the x-y plane, with the entire strength derived from flexural and membrane action in this plane. Hence, the walls of the hexcan are essentially beams in a state of plane strain. The membrane action and flexure in z direction are neglected in the accident hexcan, for energy sources are assumed to extend from 20 to 30 cm, whereas the distance across flats is only 6.9 cm, so that the effects of flexure and membrane action in the z direction should be considerably less than that in the x-y plane. Furthermore, since the energy source is considered to be centered within the energy release hexcan, no overall bending action of this hexcan is expected. On the other hand, the hexcan adjacent to the accident hexcan should exhibit substantial overall flexure, therefore beam elements in the x-y plane are not sufficient to capture the salient characteristics of its response, and beam elements are placed in the z-direction to capture the flexural resistance of the adjacent hexcan. Whereas the x-y plane beam elements constitutive characterization can be based directly on uniaxial strain tests and standard plasticity theory, these transverse beams include parameters that depend on the response and can only be determined from three dimensional experiments or analysis.

The 3D- methods have been developed in two steps. The first step was incorporated in the program REXCAT, which consists of REXCO-HT coupled with SADCAT. The REXCO [16] family of codes are two dimensional, axisymmetric hydrodynamics programs which were designed primarily for the evaluation of containment response in hypothetical core-disruptive accidents. The fluid is assumed to be compressible, inviscid, and non heat-conduction. In addition, axisymmetric shell equations are included to treat any containment. SADCAT is a finite element program for the transient analysis of thin plate and shells in three dimensional space. The numerical formulation is applicable to large deformations and elastic-plastic material models are included.

The approach used to model the accident subassembly by REXCAT is illustrated in Figure 2. The model is not exactly three dimensional, for the internals are approximated as axisymmetric. However, the three dimensional characterization of the hexcan walls is retained. The coupling thus in effect substitutes the circular cylindrical shell of the REXCO-HT code by a hexagonal duct. In achieving this coupling, it is assumed that the pressure acting on the hexagonal wall varies only with z and is uniform in any x-y plane. The validity of this assumption was checked by examining whether there are any significant pressure variations along the wall of the hexcan in the STRAW model, and it was found that for MFCI's at the center of the hexcan such variations were less than 10%.

The next step in 3D- models is illustrated in Figure 3. The same 2D-3D model as in REXCAT is used to represent the accident hexcan. The walls of the adjacent subassembly and the layer of coolant between it and the accident subassembly are also modelled in a full-blown 3D manner. The internals of the adjacent subassembly are, however, modelled only in a 2D+ sense, with a 2D model in the cross-section which passes through the center of the energy source and a 1D axial flow model which is coupled both to the 2D cross-section model and the 3D models of the walls.

The number of degrees of freedom required for this 3D- model, and hence the computational cost, is 5 to 10 times greater than that required for a 2D+ STRAW model. However, the assumptions invoked as to the nature of the response are far less severe. Thus the 3D- models serve as an invaluable means of checking some of the assumptions made in the 2D+ models.

To illustrate some features of 2D+ and 3D- solutions, a hexagonal duct is considered and REXCAT results are compared to the STRAW results. Some of the geometrical features of this problem are illustrated in Figure 4, which shows the REXCO-HT model for the source and subassembly internals, along with the SADCAT model of 1/12 of the hexagonal duct wall. Only 1/12 of the duct wall is needed because of the symmetry of the duct. The STRAW model in the x-y plane is shown in Figure 5. This mesh is used to represent the subassembly response along the entire length of the source, 22.86 cm. Above and below the source, axial flow models are used. The comparison was made using the MFCI (ANL-P) source, the details of which may be found in reference [17]. The main features of the results are compared in Table I. In addition, the pressure time history in the source zone and the time history of the displacement of the midpoint of the flat at $z = 0$ are compared in Figures 6 and 7. The displacements compare quite well. The pressure time history also are comparable, except for the magnitude of the first spike. This quantity, along with the average slug velocity, was found to depend quite markedly on the value of the lumped mass at the first node of the axial flow model. This first lumped mass of the axial flow model is generally larger than the other lumped masses because it represents the entire source region. By varying the magnitude of the mass, it was quite easy to match the REXCAT results. It appears from these results that it would be desirable to include more than one degree of freedom for the axial flow within the source region. The maximum strain at the inside wall of the corner is compared in Table I. The difference in strain and corner displacement results is believed to be due to the coarse modelling of the corner by REXCAT. Figure 8 shows the profile of the deformed hexcan as computed by REXCAT. Also shown in this figure are the midplane deformations at the flat end corner as predicted by STRAW. It should be noted, that while the corner displacement is drawn positively in this figure and in reference [11], the corner displacement in fact is negative.

An example of a REXCAT simulation of a more energetic event (.116 MJ of energy) is shown in Figure 9. With the faster rise time the deformation is confined to a smaller height but the curvature at the midplane is still quite small. Comparison of this response with STRAW shows that this is true. The midflat displacement and inside surface corner strain values are: 1.43 cm and 1.53 cm, 33% and 26%, for STRAW and REXCAT, respectively.

The running time for the 1.5 msec STRAW simulation was 2.5 minutes; it involved 7500 time steps of 0.2 microseconds. In the REXCAT solution, the running time was 15 minutes per 1.5 msec of simulation. Because the REXCAT mesh was more coarse, a larger time step (about 0.5 microseconds) was possible. Thus, the running time for the REXCAT model was 6 times that of the STRAW model; for models of equal refinement, the disparity would be even greater.

3. Modelling of Internals of Subassembly

The internals of the subassembly consist essentially of a lattice structure which is comprised of the fuel pins, their helical wire wrappers, and the coolant which occupies the voids between the fuel pins. Thus the internals are in fact a periodic, two-phase continuum which exhibits numerous complicated physical phenomena. Among these are the dispersion of wave fronts typical in composite materials, relatively large differences in effective viscosities for flow along the axis of the subassembly and normal to this axis, the complicated interaction between the fuel pins, which includes friction and the deformation characteristics of the fuel pins themselves. If only early time phenomena were of interest, it would be sufficient just to characterize the small deformation behavior at the wave front, but in safety studies response at both early and later times is of importance, so that the crushing behavior of the fuel pins must also be treated.

In the earlier studies [18], the fuel pin (that is, both the cladding and the fuel), was characterized as incompressible compared to the coolant, and the shear strength of the fuel-pin matrix was ignored. At that time, an experimental program to determine the constitutive characteristics of the fuel bundles was contemplated, and it was expected that the fuel-pin bundles would eventually be modeled by simple Coulomb-Mohr models based on the observed experimental results. However, this experimental program is still not imminent, so we have undertaken an analytical-numerical study of fuel bundles so that they can be modeled more effectively in the STRAW program. This study has focused primarily on the relationship between the forces carried by the fuel bundle and the energy absorbed by it. From these considerations, it is possible to develop constitutive equations to characterize the fuel bundles. In addition, by noting the strains in the fuel bundle associated with certain homogenized states of stress, it is possible to relate the energy deposition in the internals to the likelihood of failure of the fuel bundles.

In contrast to [4], a continuum approach has been chosen for characterizing the internals. The following are the reasons for this choice: (1) since there are 217 fuel pins per subassembly, a discrete model of the internals with a one-to-one correspondence between fuel pins and nodes would require on the order of 600 nodes (one for each fuel pin, about 3 for each of the flow channels). Experience with COBRA has shown that models of such refinement entail tremendous computational costs for the fluid flow alone, and while coarser models have proved effective in treating the fluid flow, it is doubtful that a model based on actual pin interaction would prove accurate unless the pins are treated in their actual size; (2) while it is possible to determine from experiments and analysis the overall behavior of fuel pin matrices, the determination of individual pin interactions is more difficult both experimentally and analytically.

Once a continuum approach is chosen, it is necessary to separate the behavior of the fluid from that of the fuel bundle lattice. For this purpose, the internals are represented by two layers of elements as shown in Figure 10. The fuel bundle lattice is treated by a Lagrangian mesh. The constitutive properties of the lattice are based entirely on their response in the absence of the fluid. The constitutive behavior of the fluid depends on the motion of the fluid relative to the fuel bundles and the dilatation of the mesh and fuel bundles. Therefore, it is convenient to associate a fluid element with a single pin matrix element, so a quasi-Eulerian description has been chosen for the fluid mesh.

The material properties of the fuel pin matrix are represented by a Coulomb-Mohr elastic-plastic model, so that the frictional effects of relative pin sliding are included. Though it would be desirable to establish the parameters of this material model from experiment, many of the parameters can be estimated analytically. To illustrate this procedure, consider the determination of the bulk modulus as a function of dilatation.

The compression of the fuel-bundle matrix consists of two mechanisms: (1) the decrease in distance between fuel pins which results from the twisting of the wire wraps, and flexure of the pins and (2) the decrease in the effective dimension of the fuel pin arising from deformation at the point of wrapper-pin contact.

The initial configuration of the fuel-pin matrix is assumed to be that shown in Figure 11. This configuration is repeated every 30.48 cm which is the pitch of the wire wrappers. Similar configurations with the contact points shifted 60° occur every 5.08 cm. As the bundle is compressed, the wrappers must rotate relative to the pin. The configurations of the compressed bundle every 5.08 cm, Figures 11 and 12, define the position of the wire wrap on its pin along the pitch length. With the configurations at the 60° shifted contact points identified, an expression for dilatation as a function of relative wrap rotation is found. To determine the energy associated with this dilatation, the bending of the pins necessary to achieve the decrease in volume was determined by developing configurations at various levels and deducting the shape of the fuel pin necessary to conform with these configurations. The pressure p as a function of dilatation δ is then given by

$$p = \frac{\partial U}{\partial \delta} \tag{1}$$

where U is the energy per unit volume. Comparison of these results for the initial slope of the p-δ curve agreed with the Mark CCTL Subassembly compression tests [19].

4. Summary

Analytical tools have been developed and validated by controlled sets of experiments to understand the response of an accident and/or single subassembly reasonably well. They have been subjected to a variety of loadings and boundary environments. Some large subassembly cluster experiments have been performed, however little analytical work has accompanied them because of the lack of suitable analytical tools. Reported herein are analytical approaches to: (1) development of more sophisticated models for the subassembly internals, that is, the fuel pins and coolant (2) development of models for representing three dimensional effects in subassemblies adjacent to the accident subassembly. These analytical developments will provide feasible capabilities for doing economical three-dimensional analysis not previously available.

5. Acknowledgments

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Table I. Comparison of STRAW and REXCAT Results

	STRAW (2D+ models) Model A	 Model B	 Model C	REXCAT (3D- model) Model A
Displacement of midpoint of hexcan flat (cm)	.403	.346	.390	.415
Displacement of corner (cm)	-.048	-.031	-.043	-.036
Maximum pressure in initial spike (MPa)	258.0	165.0	257.0	267.0
Maximum vaporization stage pressure (MPa)	22.8	20.0	20.0	19.6
Average slug velocity at 1 msec (cm/sec)	2840	4800	2970 5480	4940
Maximum strain at inside wall of corner (%)	7.0	6.2	6.3	4.8

Model A - sodium and fuel carried on source node

Model B - only sodium carried on source node

Model C - same as Model A except that two axial flow elements employed

Source Parameters: fuel volumetric fraction = 0.5, sodium volumetric fraction = 0.5, fuel temperature = 3115°K, coolant temperature = 672°K, fuel particle radius = 117 μm. ANL-parametric heat-transfer model was used.

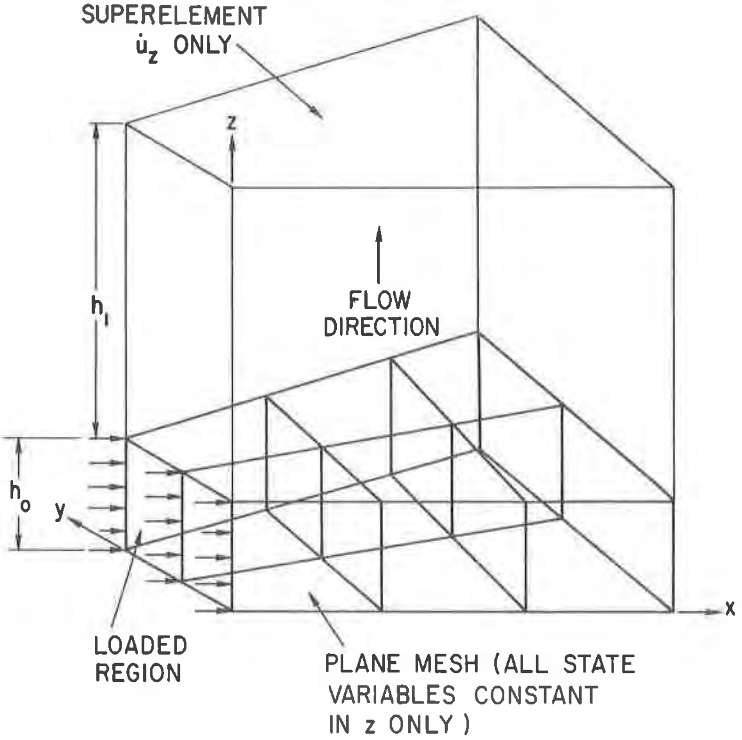


Fig. 1. 2D+ Model of the Subassembly Employed in STRAW

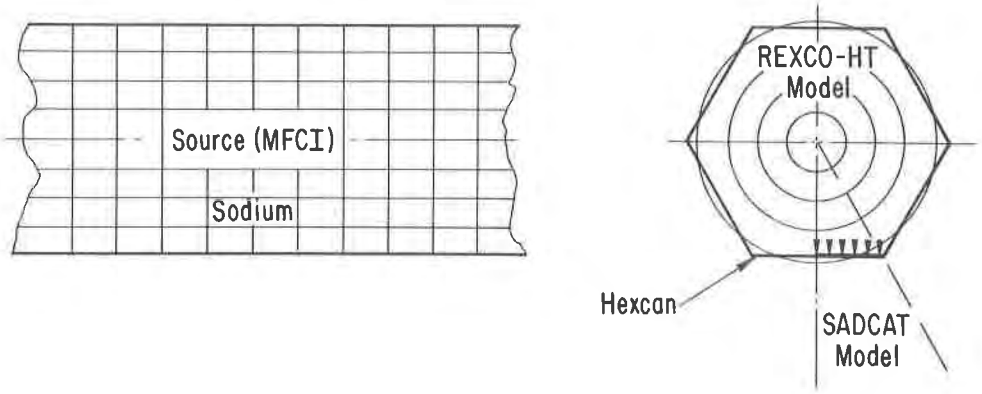


Fig. 2. REXCAT Model of the Subassembly

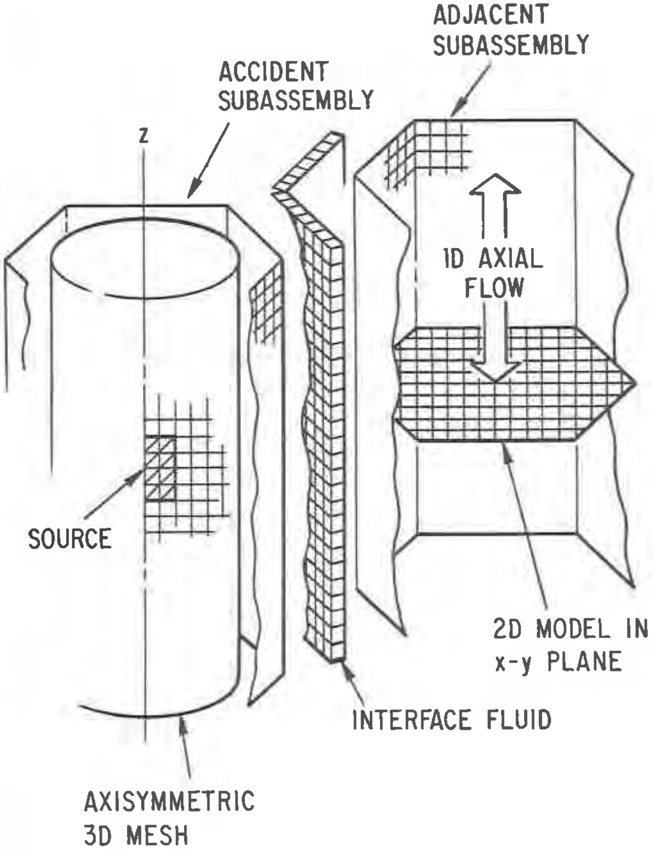


Fig. 3. 3D- Model of the Accident and Adjacent Subassemblies, Intrasubassembly Coolant and Subassembly Internals

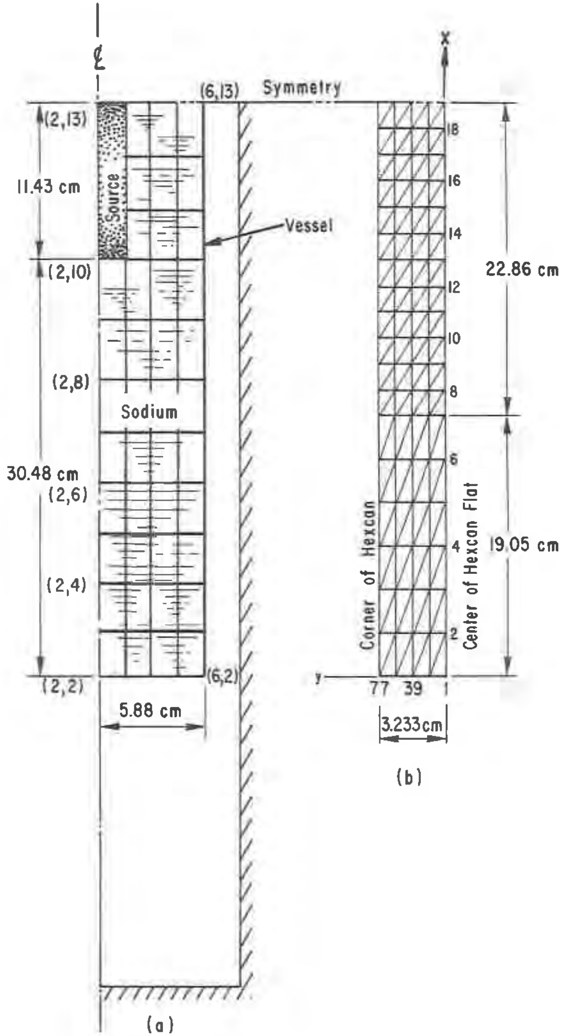


Fig. 4. REXCAT Fuel Subassembly Model for MFCI Study

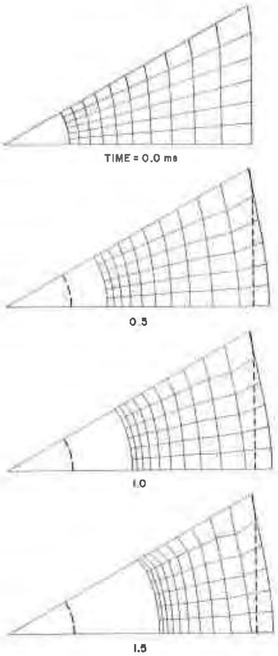


Fig. 5. STRAW Mesh in x-y Plane, Showing Both Undeformed and Deformed Meshes

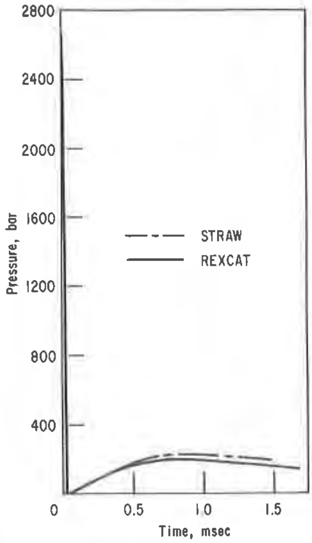


Fig. 6. Comparison of Pressure Time History in Energy Release Zone between STRAW and REXCAT

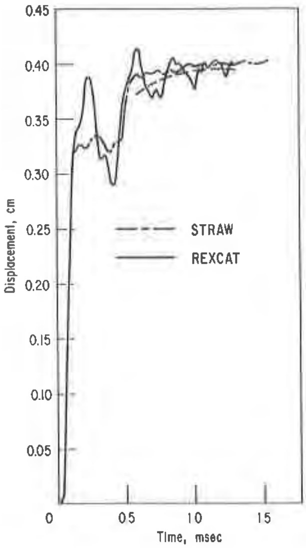


Fig. 7. Comparison of Time History of Midpoint of Flat at z = 0 between STRAW and REXCAT

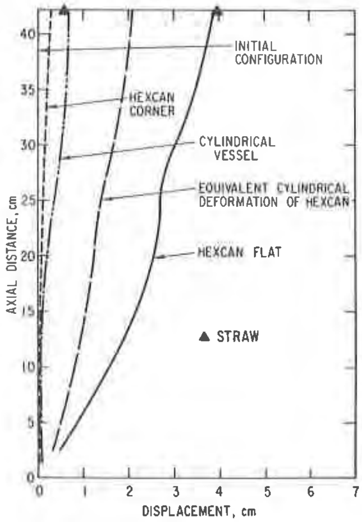


Fig. 8. Deformed Vessel Profile as Computed by REXCAT Compared to STRAW Predicted at z = 0

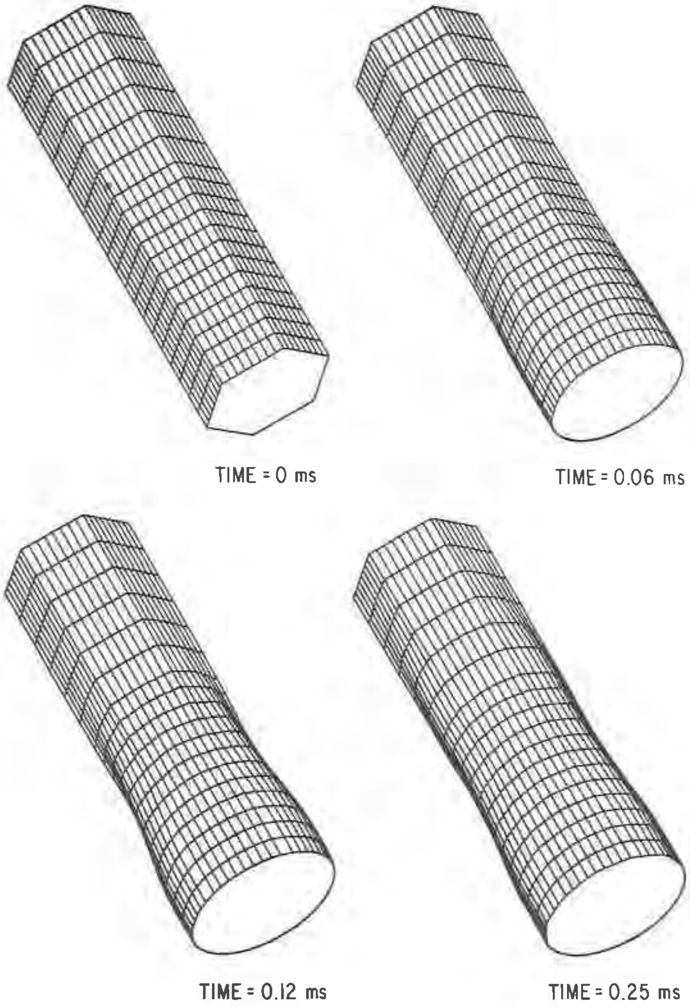


Fig. 9. REXCAT Mesh in x-y-z Plane, Showing Both Undeformed and Deformed Meshes

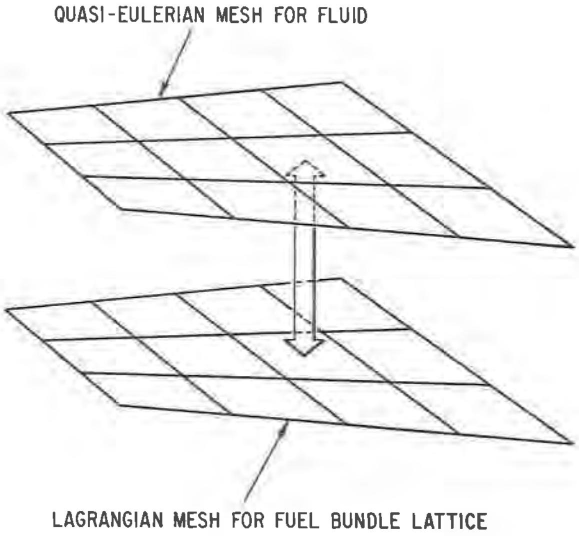
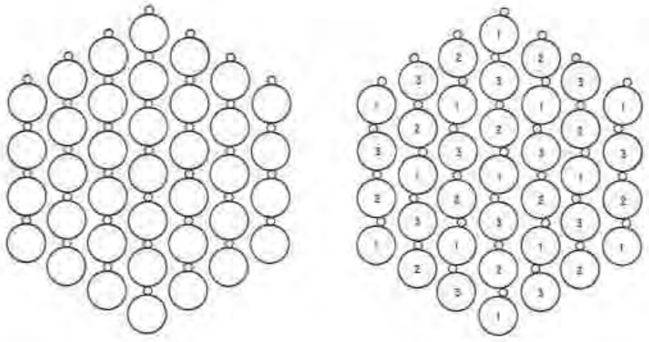
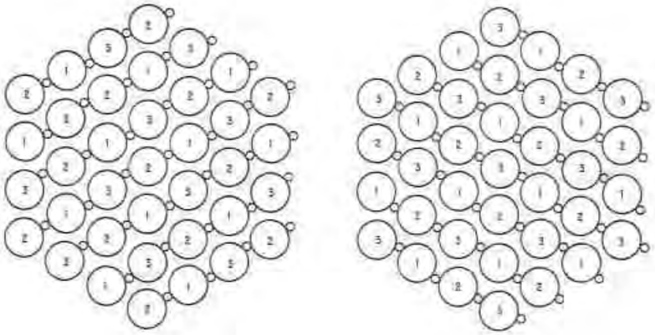


Fig. 10. Subassembly Internals Mesh Representation



Initial Uncompressed Configuration

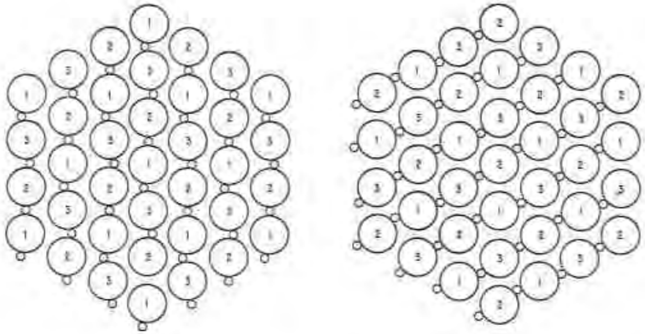
Initial Compressed Configuration



60° Shifted Compressed Configuration

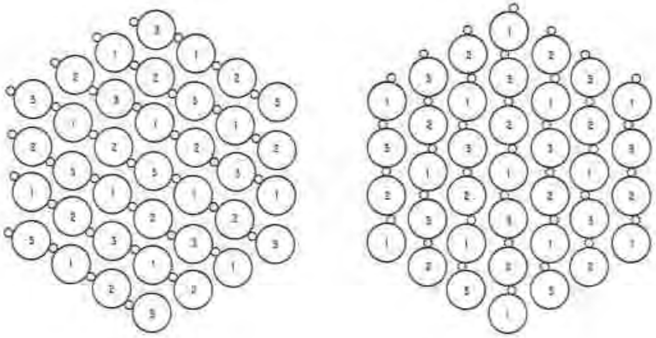
120° Shifted Compressed Configuration

Fig. 11. Fuel-pin Matrix Configuration, Part I



180° Shifted Compressed Configuration

240° Shifted Compressed Configuration



300° Shifted Compressed Configuration

360° Shifted Compressed Configuration

Fig. 12. Fuel-pin Matrix Configuration, Part II