ENERGY SOURCE AND FLUID REPRESENTATION IN A STRUCTURAL RESPONSE CODE—STRAW

T. BELYSCHKO
Department of Materials Engineering,
University of Illinois at Chicago, Chicago, Illinois 60680 U.S.A.

J.M. KENNEDY
Reactor Analysis and Safety Division,
Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

SUMMARY

In evaluating the transient response of reactor components such as fuel subassemblies, the interaction of these components with their environment plays a critical role. Preliminary studies indicate that the surrounding coolant and the adjacent subassemblies interact quite strongly with the accident subassembly, so that the response predicted in studies of an isolated accident subassembly is considerably greater than what would actually occur in the environment of the reactor, particularly for locs with rise times of 1 msec or less. Therefore, unless these surroundings are included, in design calculations or safety evaluations, the conclusions drawn are unduly conservative.

This paper describes three additional developments in the STRAW (Structural Transient Response of Assembly Wrappers) code for including the effects of surroundings:

(1) hydrodynamic finite elements, which are used to represent the plane motion of the fluid surrounding and within the subassemblies;
(2) a superimposed superelement which represents the effects of axial flow;
(3) an energy source model identical to that used in REXCO which can be used to model molten fuel coolant interactions (MPCI) or other envisioned energy release sources such as cladding-coolant interaction.

Although finite difference formulations for the hydrodynamic equations have long been available, it became apparent during the course of this development that because of the complexity of the geometry of the subassembly problem, a finite element formulation would be more suitable. This is especially true in view of the fact that the model must include several shells separated by fluid and should be easily amenable to various configurations. As a byproduct of this effort, it is now apparent that the use of a finite element formulation will permit this code to be applied to various other problems with ease.

The need for a superimposed model of the axial flow arose because of the large axial compliance of the system. The axial flow of fluid above the zones of energy release is resisted only by the viscous shear stresses exerted by the fuel pin walls and the inertia of the fluid, whereas in the cross-section the fluid is confined by the hexcan walls. Thus the energy imparted to the axial flow is often from 10 to 30 times the energy deposited in the cross-section of the energy release zones. If the axial effects are neglected and the energy is confined to the cross-section, the deformations are considerably overestimated.

The axial flow is modeled by superelements which are coupled to the two-dimensional model of the cross-section of the subassemblies. Each of these superelements can be linked to a specific part of the plane model. Thus, the axial flow can differ in the loaded hexcan, the layer of coolant between the hexcans and adjacent hexcans. The superelement can also be used to represent differing axial flows within a hexcan though neglecting any flow between adjacent superelements above the energy release plane.

Another aspect of the earlier studies that proved rather troublesome was the use of pressure-time histories to represent the loading. It was found that when adjacent rows of hexcans were added to the model, the stiffness of the system increased so that the energy imparted by the load decreased. Hence, it was difficult to isolate the influence of the surroundings from artificial effects on the loading. Since an understanding of the interaction with surrounding hexcans is essential to a successful analysis of the hexcan response problem, the subroutines for modeling energy sources in REXCO were incorporated in the program.

Results will be presented for a wide range of energy sources with maximum pressures of 137.5 bars and rise times varying from 0.10 msec to 4.00 msec. An interesting fact that emerged is that only 21% to 86% of the energy released is absorbed by the accident hexcan, with the portion increasing as the rise time decreases. The largest portion of the energy is used in driving the fluid upward.
1. Introduction

In dynamic events such as those associated with a sudden energy release in a portion of the reactor core, the transient structural response of components such as the fuel subassemblies is critically influenced by their coupling with the surrounding fluid. As shown in the previous paper by Belytschko, et al. [1] the surrounding coolant and adjacent subassemblies interact quite strongly with the subassembly in which the energy release occurs, so that the response predicted by studies of a loaded, isolated subassembly is considerably greater than would actually occur in the environment of the reactor, particularly for loads with very short rise times. Unless the influence of the surrounding coolant and adjacent subassemblies is included in the safety evaluations, the conclusions drawn are unduly conservative. Moreover, the behavior of adjacent subassemblies is of interest and importance.

The analysis of energy release events in such fluid-solid composites has customarily been carried out by finite-difference programs such as REXCO [2] and HEMP [3]. These Lagrangian finite-difference programs have reached an advanced state of development and have proven to be quite successful for relatively homogeneous configurations. However, these programs are not well suited to the analysis of complex structural configurations immersed in a fluid. HEMP, for example, includes no structural elements, so that any bending element must be represented by three to five layers of finite difference zones through the thickness. This not only brings about a need for a considerable number of elements in the analysis, but because these elements are very thin, the limitations of numerical stability in explicit integration require a very small time step. REXCO is one of the only hydrodynamic finite-difference programs that includes a structural element, but there are many restrictions on the configuration of the structure that prohibit its application to this problem.

Thus it became apparent that because of the complexity of the geometry of the core cross-sections, a finite element formulation would be most suitable. Therefore, a hydrodynamic element was added to the STRAW code described in ref.[1] along with an energy source model.

The finite element formulation for the hydrodynamic equations is sketched in Section 2; more details may be found in [4] and [5]. As shown in [5], the finite element hydrodynamic equations, when written in difference form, are identical to the equations of Wilkins [3]. The only significant difference between the finite element and difference equations is their format. The finite-difference equations of motion are written directly in terms of the stresses of the zones surrounding a mesh point, and are implemented in finite-difference programs in the same form. The finite element equations, on the other hand, are written in terms of intermediate nodal forces for both the continuum and structural elements. As a result, various types of elements may be arbitrarily combined within a mesh, so that complex geometries are easily modelled. This of course is quite advantageous in the analysis of the reactor core, since the mesh must include several subassembly walls separated by fluid and containing fluid within them.

The energy source model, which is described in Section 3, is essentially a heat transfer model combined with an equation of state for sodium. This source model is identical to the one developed for REXCO-HT [6] and it provides the code the ability to describe molten fuel coolant interactions and other possible accidents, such as cladding-coolant inter-
actions. Moreover, it provides an excellent means for studying the interaction of the accident subassembly with its surroundings. In the previous studies reported in [11], the accident was represented by a pressure time history, so that when the adjacent subassemblies were introduced in the model, the increased stiffness of the system reduced the energy delivered by the pressure source. Therefore these studies showed a decreased deformation of the accident hexagon, not only because the adjacent subassembly served as an additional means of absorbing the energy, but also because the adjacent subassemblies stiffen the system and thus reduced the energy available from a p-t curve. Since the increased stiffness of the system has markedly different effects on an energy source described by a thermodynamic process, these effects are somewhat misleading.

The STRAW program described here is essentially a two-dimensional program in which the reactor subassemblies are modelled in cross-section. Because of the large axial compliance of the system (by axial, we here mean the direction along the longitudinal axis of the fuel subassembly, perpendicular to its cross-section, as shown in fig. 1) a simple two-dimensional model is not very appropriate. The axial flow of fluid above the zones of energy release is resisted only by the viscous shear stresses exerted by the fuel pin walls and the inertia of the fluid, whereas in the cross-section, the fluid is confined by the subassembly walls. Thus the energy imparted to the axial flow may often be from 10 to 30 times as great as the energy deposited in the cross-section of the energy release zones. If the axial effects are neglected and the energy is confined to the cross-section, the deformations are of course overpredicted. Because a complete three-dimensional model would be hopelessly uneconomical for computer solution, a one-dimensional, axial flow model coupled to the two-dimensional model of the cross-section was developed. The procedure was first described in [11], in Section 4 several aspects of it are reviewed and some new developments described.

The results described in this paper deal mainly with the partitioning of the energy released by the source among the axial flow, the accident subassembly, and the adjacent subassemblies. The influence of factors such as rise time, peak pressure, and duration of the accident have been studied. These results are reviewed in Section 5. The work reported here is part of a rather comprehensive effort to develop models for subassembly response and include a program of experiments and experimental-analytical comparisons; the latter is described in this conference in [7].

2. Hydrodynamic Finite Element

The two-dimensional hydrodynamic element has been programmed with the option of three geometries: triangular, quadrilateral, and pentagon (see fig. 2). Meshes consist mostly of quadrilateral elements. Triangles are used where needed in irregular geometries, and when corners in a mesh are very sharp, pentagons are used so that the stability limit on the time step is not too small.

The discrete equations of motion are obtained by an energy approach which in this case is equivalent to a Galerkin approach. Because of space limitations, we refer the reader to [8] for more details on the finite element equations. In brief, the equations of motion are

\[ [M] \dot{\mathbf{u}} + [F_{\text{int}}] = [F_{\text{ext}}] \]  

(1)

where \([M]\) is the mass matrix, \([\mathbf{u}]\) the matrix of nodal displacements, \([F_{\text{ext}}]\) the matrix of discrete external forces, and \([F_{\text{int}}]\) the forces arising from the resistance of the continuum
to deformation; superscript dots denote time derivatives. The internal nodal forces at any node are obtained by summing the appropriate nodal forces of all adjacent elements. The rate of work of the discrete nodal forces must equal the work in the element for arbitrary nodal velocities, so for an element \( j \)

\[
{\{u\}}_{j}^{T} \{f^{\text{int}}\} = \int_{V(j)} \rho \dot{e} dV
\]

(2)

where \( \rho \) is the density, \( e \) the internal energy and \( V \) the volume of the element; \( \{f^{\text{int}}\} \) is the matrix of internal nodal forces for the element, which consists of the following terms:

\[
\{f_{x1}^{1}, f_{y1}^{1}\} \text{ to } \{f_{x5}^{n}, f_{y5}^{n}\}, \text{ where } n = 3, 4, \text{ and } 5 \text{ for the triangle, quadrilateral and pentagon, respectively; } I \text{ are the node numbers, and all nodes are at the corners of the elements. If we use the identity }
\]

\[
p_{0} = - \frac{p}{J} \frac{J}{j}
\]

(3)

where \( p \) is the pressure and \( J \) the Jacobian between the deformed and undeformed element, we obtain

\[
{\{u\}}_{j}^{\cdot T} \{f^{\text{int}}\} = - \int_{V(j)} \rho \frac{\dot{e}}{J} dV = - \int_{V(j)} \rho \frac{\dot{e}}{J} dV
\]

(4)

We now make the assumption that the pressure \( p \) is constant within each element. This assumption is necessary if the equation of state is to be evaluated at only a single point in the element, which is of course desirable for computational efficiency. This approach does lead to problems of mesh instabilities, such as the hourglass phenomenon, but these can be dealt with; see [4]. Equation (4) then can be simplified to

\[
{\{u\}}_{j}^{\cdot T} \{f^{\text{int}}\} = - p \int_{V(j)} \frac{\dot{e}}{J} dV = - p \frac{\dot{e}}{J} \frac{V(j)}{V(j)}
\]

(5)

The rate of velocity change can be expressed as a linear function of nodal velocities in the form

\[
\frac{\dot{V}}{V(j)} = [B] \frac{\dot{u}}{u}_{j}
\]

(6)

Substituting Eq. (6) into Eq. (5), we obtain

\[
{\{u\}}_{j}^{\cdot T} \{f^{\text{int}}\} = \frac{\dot{p}}{p} \frac{\dot{u}}{u}_{j} {\{u\}}_{j}^{T} [B]
\]

(7)

Since the consistency in energy must hold for arbitrary nodal velocities, it follows that

\[
{\{f^{\text{int}}\}}_{j} = -p [B]
\]

(8)

For the triangle, quadrilateral and pentagon, the volume \( V \) are given, respectively, by

\[
V = \frac{1}{2} (x_{21}y_{31} - x_{31}y_{21})
\]

(9a)
\[ V = \frac{1}{2} \left( x_{21}y_{31} + x_{31}y_{41} - x_{31}y_{21} - x_{41}y_{31} \right) \]  

\[ V = \frac{1}{2} \left( x_{21}y_{31} + x_{31}y_{41} + x_{41}y_{31} - x_{31}y_{21} - x_{41}y_{31} - x_{51}y_{41} \right) \]

where

\[ x_{1J} = x_I - x_J \]
\[ y_{1J} = y_I - y_J \]

These coordinates are the current coordinates of the nodes.

Taking the time derivatives of the volume \( V \), noting that the time derivatives of the coordinates are the velocities, and comparing with Eq. (6), we find that [B] is respectively given by

\[ [B] = \frac{1}{2} \left[ y_{23}, x_{32}, y_{31}, x_{13}, y_{12}, x_{21} \right] \]

\[ [B] = \frac{1}{2} \left[ y_{24}, x_{42}, y_{31}, x_{13}, y_{42}, x_{24}, y_{13}, x_{31} \right] \]

\[ [B] = \frac{1}{2} \left[ y_{25}, x_{52}, y_{31}, x_{13}, y_{42}, x_{24}, y_{53}, x_{35}, y_{14}, x_{41} \right] \]

The equations of motion are integrated by an explicit, central difference method. Hence at any time step, the coordinates are known, and the new volumes can be computed by Eqs. (9) (actually an equation in terms of the original coordinates and displacements of the nodes is used to reduce roundoff errors). The pressure in each zone is computed by the equation of state, and the nodal forces by Eq. (8). The element nodal forces are then summed appropriately to find \( F^{int} \), and the accelerations are found by Eq. (1). The accelerations are then integrated to find the new coordinates of the nodes. Structural elements, such as beams, are treated in an identical fashion using nodal force equations derived in [7]. A 5000 element mesh of hydrodynamic elements requires about 1 second of IBM 370/195 computer time per time step.

3. Energy Source

The energy source is the quasi-steady-state-model described in [6], which will here be summarized. The model assumes that the energy release zone consists of a specified fraction, \( w \), of a solid at a given initial temperature mixed with sodium. The solid is fragmented and a characteristic radius for the solid, \( r \), must be specified. The heat transfer rate from solid to sodium, \( \dot{q} \), is then taken to be

\[ \dot{q} = \frac{3wR}{\rho_s} \left( T_s - T \right) \]

where \( k_s \) is the thermal conductivity of the solid and \( \rho_s \) its density; \( T_s \) and \( T \) are the current temperatures of the solid and sodium, respectively. The melting and associated heat of fusion of the solid are included in the analysis.

The equation of state of the energy zone is governed by the sodium and any fission gas present; the solid is assumed to be incompressible. The fission gas is assumed to be
at the same temperature as the sodium. The equation of state for the sodium treats both the liquid phase and the two-phase (liquid-vapor) behavior of the sodium.

4. Axial Flow

The model of the reactor core is schematically illustrated in Fig. 1. The hexacan walls and fuel pins are aligned vertically in the z-direction, and the two-dimensional discrete model represents the \( x-y \) plane, a cross-section of part of the core. The energy release and pressure are assumed to be distributed over a height \( h_o \) and uniform with \( z \). To represent the axial flow, a one-dimensional flow model is coupled to the discrete \( x-y \) model. Thus, the model may be viewed as quasi-three-dimensional.

The model treats the fuel pins and fuel as an inert, incompressible constituent, accounting only for the compressibility of the sodium. The shear strength of the fuel pin structure is neglected, although techniques for its representation are under development.

Let \( \rho_p \) and \( \rho_o \) be the fluid and solid densities, \( \text{V}_p \) and \( \text{V}_o \) the volumes of the fluid and solid, and \( \Delta z \) be the displacement of the interface between the plane and the axial flow models.

Since the solid is incompressible, it follows that

\[
(\rho_p + \Delta \rho_p) (V_p + \Delta V_p) = \rho_o V_o
\]

(12)

where subscript noughts designate the initial values and prefix deltas designate the total change from the initial value. The fluid area is constant vertically so

\[
V_p = A_p z = r_p \Delta z
\]

(13)

where \( r_p \) is the fluid volume fraction and \( A \) the total cross-sectional area.

\[
\Delta V_p = \Delta A_o + r_p A_o \Delta z + \Delta A \Delta z
\]

(14)

From eqs. (12) and (14), it follows that

\[
\Delta \rho_p = \rho_o \left( \frac{\Delta A_p}{r_p A_o \rho_o} + \frac{\Delta z}{z_o} + \frac{\Delta A \Delta z}{r_p A_o} \right) \frac{1}{1 + \frac{\Delta A}{x_o} + \frac{\Delta z}{x_o} + \frac{\Delta A \Delta z}{r_p A_o}}
\]

(15)

If we neglect second order effects and divide both sides of eq. (15) by \( \Delta t \), we recover the rate expression given in ref. [1].

The density obtained from eq. (15) is used for both the equation of state in the \( x-y \) plane and the one-dimensional axial flow model in the \( z \)-direction. At any time step, the change in area, \( \Delta A \), is obtained from the \( x-y \) model, while \( \Delta z \) is obtained from the axial model. The axial model is driven by the pressure in the \( x-y \) plane.

Equation (15) is valid only when

\[
\Delta V_p > \text{V}_o
\]

(16)

Otherwise, eq. (15) indicates \( \Delta \rho_p > 0 \), which is quite unrealistic for the compressed zone. This difficulty arises because the violation of eq. (16) contradicts the original assumption that the solid is incompressible. Although the pressure would rise dramatically before eq. (16) is violated, it is possible through local instabilities to violate eq. (14); provisions are included in the equation of state to preclude this difficulty.

Similarly, any calculations in which
\[ \Delta A_F > -\Delta A_{Po} \]  

(17)

are unrealistic for they imply that the incompressible solid has no shear strength.

5. Examples of Results

We will give examples from three studies: (1) a study on the effect of surroundings for weak accidents; (2) a study on the effect of pressure rise times; (3) a computation for the response of a complex model to a strong energy release.

For the first study, the mesh shown in fig. 3 was used. The energy source was modeled in the center of the accident subassembly, so a 1/12th model was used. The central zone represents the fuel coolant interaction (FCI) zone for an assumed accident in a region that would usually be occupied by seven fuel pins; it was modeled by an element with uniform pressure. The subassembly walls were represented by beam elements. A single axial flow model was used to represent the axial flow in the accident subassembly. The following properties of the stainless steel and liquid were used. The elastic modulus of steel was $1.62 \times 10^{12}$ dynes/cm$^2$; the yield strength $3.93 \times 10^9$ dynes/cm$^2$; the plastic modulus $2.379 \times 10^{11}$ dynes/cm$^2$; all values were corrected for plane strain as indicated in [1].

Two models were used: an isolated model consisting only of the elements up to and including the hexcan wall (H), and an extended model (E) consisting of the mesh shown in fig. 3. The initial conditions for the FCI are given in Table I, and some results are tabulated in Table II.

As can be seen from the table, the effect of the environment of the hexcan is to reduce the energy imparted to the accident hexcan by about 50%. In the extended model, only 2 to 6% of the energy is absorbed by the accident hexcan. Unlike in ref. [1], these comparisons between isolated (H) and more complete models (E) are in each case for similar energy sources. While the energy imparted decreases for a given pressure-time curve as the stiffness of the system increases, for an FCI model the energy increases. Yet the net effect is still a substantial reduction in the accident hexcan deformation.

In the accidents reported in Table II, the rise times to maximum pressure are on the order of 5 msec. Table III illustrates the effect of the rise time. The model used here was identical to that used in the previous study for the isolated hexcan (H), except that a pressure time history was input at the boundary of the FCI region. The input in each case was a triangular time history with identical decay and rise times. As can be seen from the results, for short loads a much larger portion of the energy is absorbed by the accident subassembly.

A more complex model was developed to study the interaction of several rows of subassemblies to an arbitrary strong energy release: a triangular pressure pulse of 0.40 msec width with equal rise and decay times and 687.5 bars peak. The complex model mesh is shown in fig. 4 along with the deformed mesh at 0.25 msec. For this simulation, it is seen that most of the deformation occurs in the frontal half of the adjacent subassembly. The fact that there is small deformation elsewhere is due to the strong axial pressure relief from the axial flow model; the fluid volume fraction is 1.0. More extensive analysis of this model is in progress.
### TABLE I

Initial Conditions for FCI

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuel Temp (°K)</th>
<th>Coolant Temp (°K)</th>
<th>Fuel Volumetric Fraction</th>
<th>Sodium Volumetric Fraction</th>
<th>Gas Volumetric Fraction</th>
<th>Half Height FCI Zone h₀ (cm)</th>
<th>Height Axial Column (cm)</th>
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<tbody>
<tr>
<td>H1, E1</td>
<td>3115</td>
<td>672</td>
<td>.5</td>
<td>.5</td>
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<td>.475</td>
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### TABLE II

Energy Partition Results at Peak Flat Midpoint Displacement (One-twelfth Values)

<table>
<thead>
<tr>
<th>Case</th>
<th>Peak Pressure (bars)</th>
<th>Maximum Flat Midpoint Displacement (cm)</th>
<th>Maximum Strain Inside Corner Surface (cm/cm)</th>
<th>Accident Hexcan Internal Energy per Unit Height (Joules/cm)</th>
<th>Accident Hexcan Internal Energy Percent of Total Energy (%)</th>
<th>Adjacent Hexcan Internal Energy per Unit Height (Joules/cm)</th>
<th>External Energy per Unit Height (Joules/cm)</th>
<th>Total Axial Energy (Joules)</th>
<th>Total Axial Energy Percent of Total Energy (%)</th>
<th>Axial Interface Velocity (cm/sec)</th>
<th>Axial Interface Displacement (cm)</th>
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<tr>
<td>H1</td>
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<td>3.23</td>
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### TABLE III

Energy Partition for Isolated Hexagon Geometry with Pressure History Supplied (One-twelfth Values)

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<tr>
<th>Case</th>
<th>Peak Pressure (bars)</th>
<th>Peak Pressure Rise Time (msec)</th>
<th>Maximum Flat Midpoint Displacement (cm)</th>
<th>Maximum Strain-Inside Corner Surface (cm/cm)</th>
<th>Accident Hexagon Internal Energy per Unit Height (joules/cm)</th>
<th>Accident Hexagon Internal Energy Percent of Total Energy (%)</th>
<th>External Work per Unit Height (joules/cm)</th>
<th>Total Axial Energy (joules)</th>
<th>Total Axial Energy Percent of Total Energy (%)</th>
<th>Axial Interface Velocity (cm/sec)</th>
<th>Axial Interface Displacement (cm)</th>
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References


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Fig. 1 Schematic of Subassembly problem model; x-y plane is cross-section perpendicular to axes of subassemblies and fuel pins.

Fig. 2 Hydrodynamic element geometry and nomenclature

Fig. 3 Mesh for extended model studies (E); isolated hexcan mesh (H) is a subset of this mesh consisting of the region from the FCI to first hexcan wall.
Fig. 4 Undeformed geometry and deformed geometry at .25 msec for mesh.