NONLINEAR TRANSIENT DEFORMATION OF LMFBR FUEL ELEMENTS UNDER IMPULSIVE LOADING

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SUMMARY

Hypothetical reactor accidents are characterized by a sudden release of substantial thermal energy in one fuel element. Presently it cannot be excluded that for instance pressure pulses due to a fuel coolant interaction may have such time scales and impulses as to deform neighboring subassemblies permanently. Additionally coherent fuel element motion may limit control rod scram action and possibly cause untolerable reactivity increases. Therefore LMFBR safety requires to analyze the complex mechanical response of the core structure under typical loading conditions. An important contribution to this problem is to examine the nonlinear structural dynamics of an individual fuel element under prescribed loading and boundary conditions. Subject of this paper is the elastoplastic transient behavior of one subassembly under given space- and time-dependent pressure loading. The interaction of several colliding fuel elements including coolant dynamics is briefly discussed.

Theoretical Models: Description is given of important physical mechanisms (bending of the slender subassembly duct, flattening of the thin-walled hexagonal cross section, pin-bundle and coolant action). Then discrete structural models of different levels of refinement are compared and applied to the coupled fluid-structure problem. In particular the use of a special beam element with lumped masses and discrete elastoplastic "hinges" with concentrated moments allows the effective simulation of the structure. The outlined model handles material and geometric nonlinearities, arbitrary time-dependent nodal loading and/or prescribed boundary motions due to collision. When satisfying compatibility the principle of virtual work is shown to yield the set of differential equations of motion. External forces arising from coolant dynamics due to structural motion are analyzed with an incompressible Eulerian nonstationary flow model including friction. The final nonlinear vector differential equation is solved by a 4th order variable step Runge-Kutta method.

Static and Impact Experiments: A reliable assessment of the core deformation problem necessitates experimental verification of the outlined theoretical models and underlying hypotheses. Description is given of a single subassembly experimental program on a special drop-tower facility which is used for static and impact loading of 1:1 SNR-300 type fuel element models. Also described is a load and impact controlling device utilizing honeycomb crushing material which allows to produce desired pressure pulses (rise time, peak load, impulse, pulse shape). Forces, accelerations and strains are measured at the subassembly; its deformation is filmed with a high-speed camera and recorded by specially designed photodiode-arrays. The purpose of the experiments is to establish elastoplastic force-deflection characteristics and energy absorption capabilities under varying conditions. Typical results are shown, discussed and compared to computer predictions.

Results and Conclusions: Good agreement is observed between experimental and theoretical response data. Parameter studies confirmed the significant role of duct flexure, local cross section flattening, material ductility and strain-hardening. The stiffening effect of the combined deformation of pin-bundle and spacer-grids is very strong, and most of the energy is dissipated by localized yielding of the hexcan. Sample results are presented concerning the dynamic response of several interacting subassemblies with coolant in between, and a considerable ability of energy absorption i.e. confinement of deformations is concluded.

1. Introduction and Scope

Some LMFBR core accidents are characterized by a sudden release of excessive thermal energy in one of the clustered fuel elements. Presently there are uncertainties about possible release mechanisms such as molten fuel-coolant interaction (MFCI) involving coolant vaporization and fuel fragmentation [1]. It cannot be excluded that resulting pressure pulses have such peaks, impulses and durations as to rupture the incident subassembly and deform adjacent fuel elements permanently. This coherent and significant motion of core internals may disturb control rod scram action and lead to untolerable reactivity increases. Therefore a satisfactory safety analysis has to demonstrate that the escalation of such single subassembly failure situations to a whole core accident is very unlikely and that the reactor can be shut down in time [2]. General and reliable numerical methods are being developed and verified by experiments to assess the deformation problem of a transiently loaded core [3, 4, 5]. The basis of this effort is the nonlinear structural dynamics of one fuel element under given time dependent loading. This is the main subject of this paper (see also papers E 2/1* and E 2/2 of this conference). Most of the work published [6, 7, 8] on the transient elastoplastic response of a single subassembly examines the hexagonal wrapper as a shell under constant boundary conditions. Little is known about its interaction with the complex pin-bundle inside the wrapper and the restraining effect of the coolant motion between colliding fuel elements. In addition there is no experimental data available about single subassembly behaviour which is necessary for realistic code development as well as understanding and generalization of costly full-scale core explosion test [3]. Here description and application is given of discrete structural and fluid models developed for the analysis of a single subassembly under general time dependent loading and/or boundary conditions. It is also shown how to assess the coupled motion of several fuel elements and the surrounding coolant. Then experiments are described involving static and impulsive loading of single fuel elements. Test results are shown to support theoretical assumptions and improve core deformation predictions for large future LMFBRs.

2. Problem and Theoretical Simulation

In contrast to longtime operational performance of fuel elements with creep and swelling [9] impulsive accident loading causes high inertia forces and large nonlinear deformations. The structural response due to transverse loading involves bending of the slender subassembly duct as a beam and flattening of the thin-walled hexcan as well as pin-bundle deformation indicated in Fig. 1 and 6. These three mechanisms described in [10] cause relative displacements in the core giving rise to forced coolant motion with corresponding fluid backpressure. A complete theoretical analysis of these coupled phenomena in the complex 3D core geometry is a virtual impossibility. Therefore properly chosen discretizations in space and time are mandatory. Refined simulation of even one complete fuel element by usual shell elements requires a large number

of degrees of freedom. Consequently code development for multirow core analysis becomes critical. For this goal simpler mechanical models are necessary which simulate the dominating phenomena without loosing generality. To recognize these phenomena basic experiments are required on single subassembly behaviour to justify hypotheses and find out the relative significance of various effects.

A straightforward simulation of the transiently loaded core structure is achieved by employing equivalent mass-spring-dashpot arrangements with given, driving forces or accelerations. The continuous structure is replaced by an array of discrete masses interconnected by nonlinear spring- and dashpot-mechanisms with experimentally or analytically determined characteristics. As an example Fig. 5 shows a "spoke" model representing a series of interacting fuel elements separated by thin layers of coolant. Models on this basis were extensively used for transient response calculations of single as well as multiple fuel elements [10]. Deformation results tend to be conservative and the versatile method can be readily extended. However, additional information is needed on modes of deformation, nonlinear effects etc. to set up the equivalent discrete system.

A more refined and general simulation of elastoplastic dynamic systems was performed using a special beam element characterized by lumped masses and discrete elastoplastic "hinges" which are located at the nodal mass points j in Fig. 1. Bending moments are calculated at these hinges/nodes which are connected by massless, straight, extensible or rigid links. Nonlinear moment-curvature expressions were obtained from bilinear stress-strain representations employing elastoplastic beam theory (Fig. 4). 2D kinematics of nodes and links are described by generalized coordinates in a fixed reference system. Using the principle of virtual work in its general form

$$\sum_j \{ F_p^j - F_r^j - \frac{d}{dt} (\dot{x}^j m^j) \} \{ \delta x^j \} = 0 \qquad (1)$$

for nonconservative systems and varying the generalized coordinates x^j in agreement with the boundary conditions yields the set of dynamic equilibrium equations. This procedure proved to be superior to a finite difference approach similar to [11]; it is more flexible in treating time dependent boundary conditions, which occur during collision of fuel elements. Another advantage is that practically the same equations of motion can be used for arbitrarily dynamic and even quasistatic conditions. In all cases a 4th order variable step Runge-Kutta integrator [12] was applied to the explicit set of equations. The coefficients of this system of nonlinear differential equations and their degree of coupling vary with time, nodal displacement and velocity. This is due to geometric and material nonlinearities including strain-hardening, unloading, rate-effects (Fig. 4) and also due to forces resulting from coupled coolant dynamics and/or bundle interaction or subassembly collision. Fig. 4 shows typical results of a transient elastoplastic hexcan res-

ponse analysis.

Coolant motion induced by structural displacement is simulated by an incompressible nonstationary flow model including friction. Fig. 2 shows five fuel elements in a 30 ° sector around the ruptured subassembly. The liquid sodium in the gaps between the elements is squeezed out essentially moving in the plane shown. Similar to [13] a 2D fluid flow network is set up consisting of total pressure nodes which are connected by time dependent branch flows as indicated in Fig. 2. The nonstationary inertial and frictional flow through each branch with parallel walls is described by Euler's equation of motion:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial \xi}\right) = - \frac{\partial p}{\partial \xi} - \left(\frac{\lambda_T}{2D_h}\right) u^2 \, \mathrm{sgn}(u) \qquad (2)$$

Three flow phases are distinguished in each branch with prescribed time dependent motion of both walls: coolant squeezing, zero motion (subassembly contact) and coolant suction. Conservation of fluid mass and energy at each node determines the flow and pressure boundary conditions across each branch. Finally coolant pressures are integrated along each branch to get resulting fluid forces. These forces are acting as additional external loads on the structure, which assures the simulation of structure-coolant interaction.

3. Experimental Work

To verify the outlined theoretical models and assumptions a series of single subassembly experiments is performed [10]. The purpose of these tests is to study the nonlinear deformation behaviour of complete 1:1 fuel element models under static and impulsive transverse loading (Fig. 6). In particular force-deflection characteristics and energy absorption capabilities are established from different SNR-300 type subassemblies under varying boundary and loading conditions. A special drop-test facility described in [5, 10] was built allowing to produce static (hydraulic) or dynamic forces (falling mass) at the specimen. Properly sized honeycomb crushing material is used between the drop weight and the loading pad resting on the subassembly. This allows to limit impact forces and pulse durations to the desired range of 10^4 - 10^5 N and 10 - 100 millisec, respectively. Forces, accelerations and strains are measured at the fuel element. The duct bending and cross section flattening deformation is filmed with a high-speed camera and separately recorded by specially designed photodiode-arrays without delay. First dynamic tests are presently analyzed; typical static test results are shown in Fig. 3 and compared to 2D elastoplastic calculations obtained with the outlined lumped parameter hinge model. The strongly nonlinear behaviour of the dissipative system pin-bundle/spacer-grids inside the hexcan is treated as a compressible fluid in this analysis. Important information on the frictional interaction of bundle and hexcan is extracted from this type of experiment. Fig. 6 shows loading pad, force and deflection pick-up as well as modes of duct bending deformation after static and dynamic testing.

A very important input information for the codes are the hexcan material laws. Static tension tests provided base data on three wrapper materials at different temperatures. Split-Hopkinson-bar tests are performed in cooperation with Euratom/Ispra to obtain realistic stress-strain- strain rate-behaviour which will be compared to the static control tests.

4. Results and Conclusions

Theoretical models and supporting experiments were described which allow to analyze the transient elastoplastic deformation of single and multiple LMFBR type fuel elements. Sample results are given in Fig. 3, 4, 7. For the single subassembly behaviour the following conclusions can be summarized concerning model capabilities and experimental findings:

- Nonlinear load-deflection calculations of empty hexcan cross section under quasistatic prescribed flattening rates were confirmed by experimental data (Fig. 3). Growth of plastic zones and formation of hinges in the corners characterize the postelastic deformation.
- The complex behaviour of the pin-bundle inside a hexcan is dominated by a progressively frictional distortion of the spacer-grids between the large number of displaced pins (Fig. 3). Analytical bundle models have to account for these dissipative effects. Spacing of the spacer-grids strongly influences the stiffening effect of the bundle inside the can.
- The hexcan crushing strength is proportional to $(s/d)^3$ according to the dominating bending deformation of the flats (see Fig. 3). Membrane deformations i. e. extensions of the flats due to bundle action are neglegibly small. A distinct interaction of duct flexure and local cross section deformation was experienced in both static and dynamic subassembly tests (Fig. 6). Hexcan flattening and local buckling greatly reduces the bending stiffness of the fuel element.
- 2D transient response analysis of the reference case "pinned hexcan" in Fig. 4 provided nodal displacement-, velocity- and acceleration-histories due to the assumed force pulse F(T). Simultaneous work calculations demonstrate energy partition and absorption by plastic structural work. Parametric studies indicate the significance of strain-hardening in the corners, yield stress level, loading impulse and pulse shape on permanent deformation.

First numerical results on multiple fuel element response were reported in [10]. An extended "spoke" model (Fig. 5) including coolant dynamics was used for 4-row core calculations. Fig. 5 shows pressure histories extracted from records of an SNR-300 core model explosion test. Forcing functions due to these pulses together with experimentally obtained subassembly force-deflection characteristics were employed for a transient core analysis. The following conclusions can be summarized from sample results in Fig. 7 and other calculations:

- Permanent deformations are reasonably well agreeing with explosion test data. Plastic cross section flattening is confined to the 1st row and considerable subassembly bending remains essentially elastic.
- The cushioning effect of coolant layers between the elements reduces impact forces. Energy dissipation and dispersion by fluid motion is relatively small as compared to structural work
- Deformations, velocities, accelerations and forces are rapidly decaying with distance from the ruptured subassembly.

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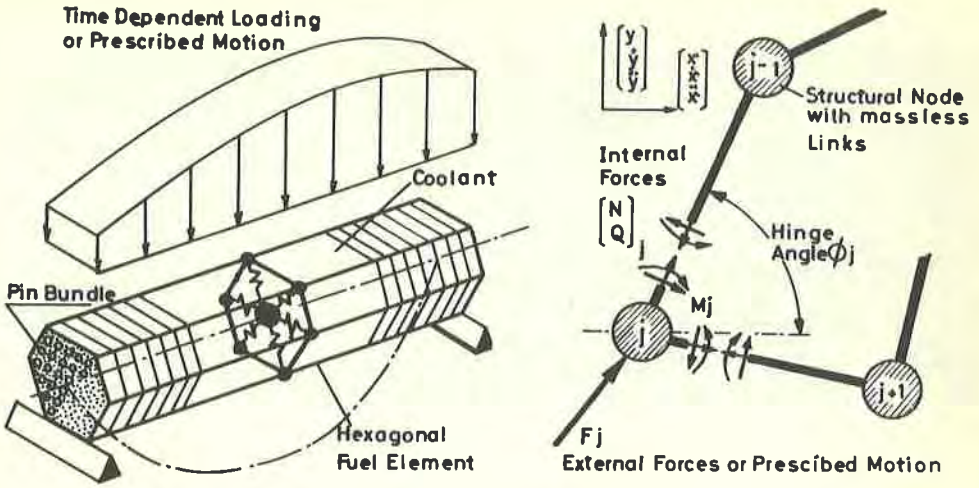


Fig. 1 Lumped Parameter Hinge Model for Nonlinear Structural Dynamics

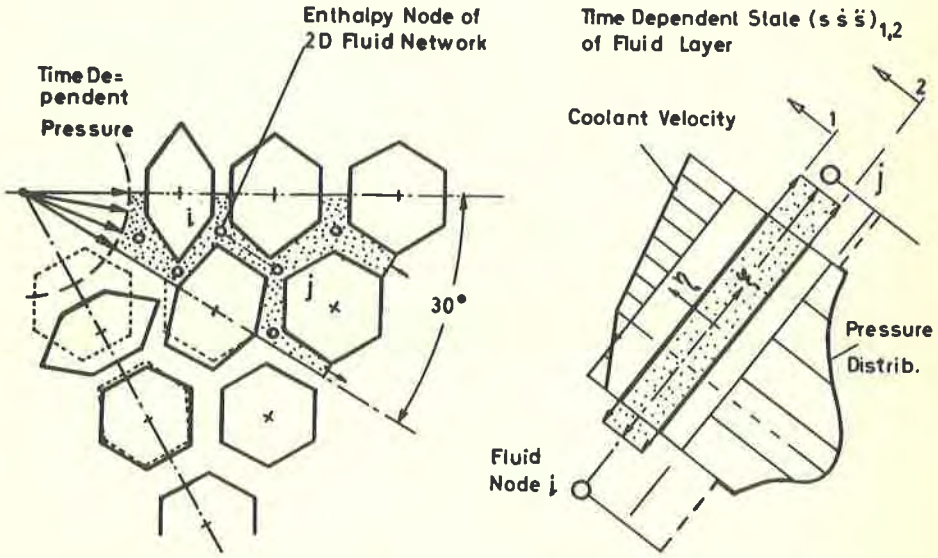
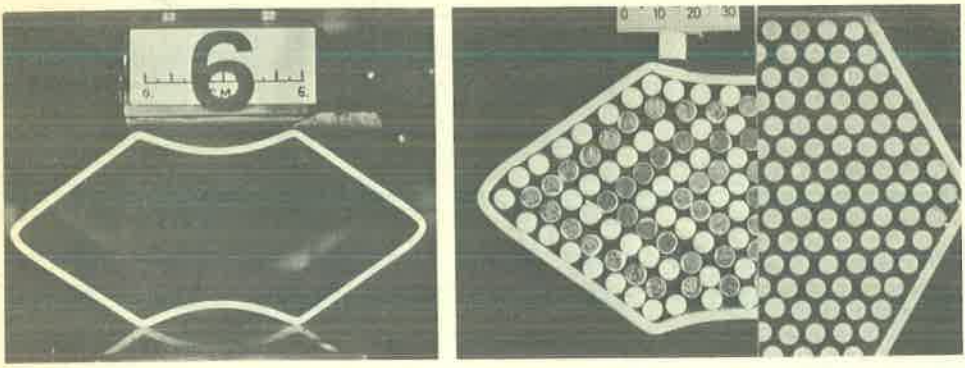


Fig. 2 Fluid Flow Model for Coolant Dynamics



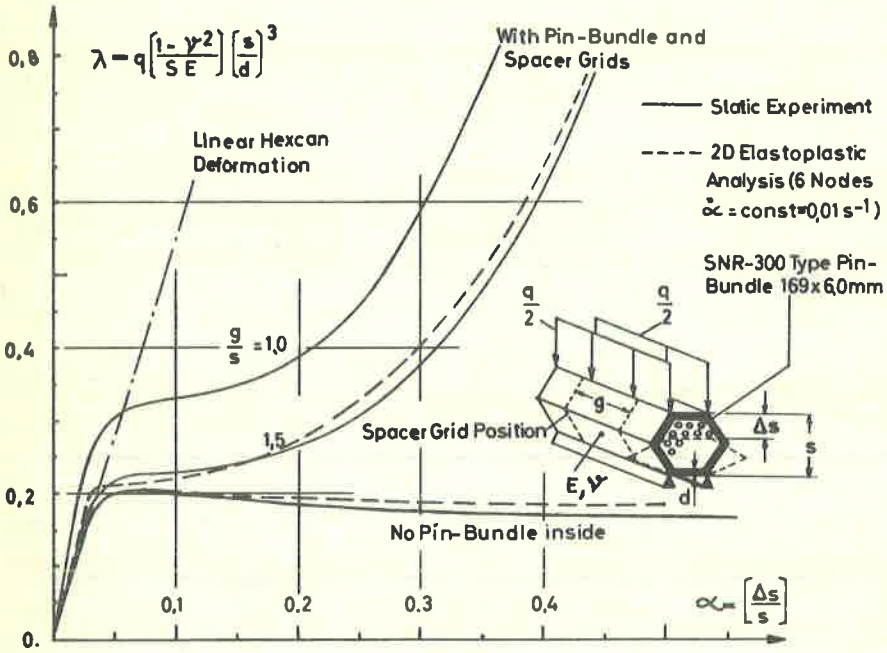


Fig. 3 Plain Strain Deformation Results of a Fuel Element Model under Quasistatic Loading

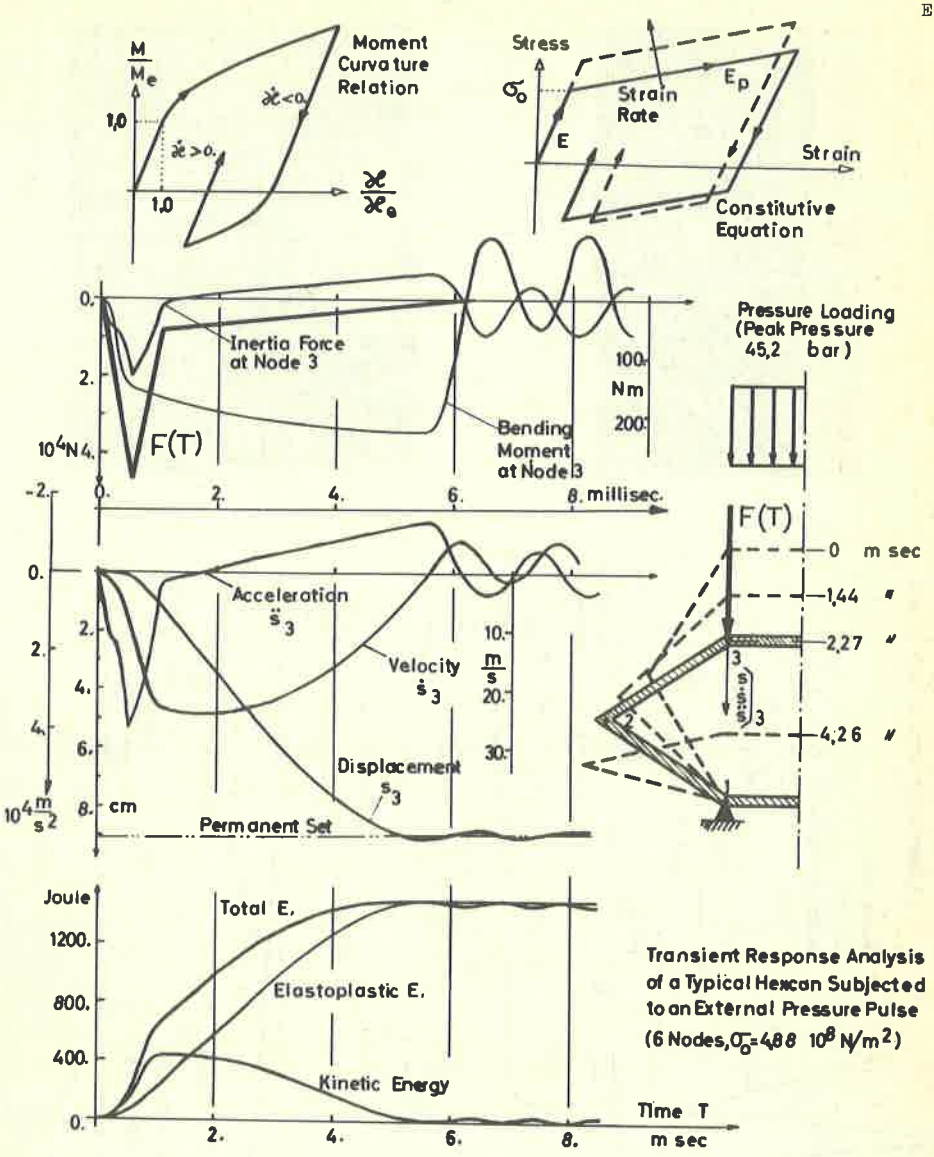
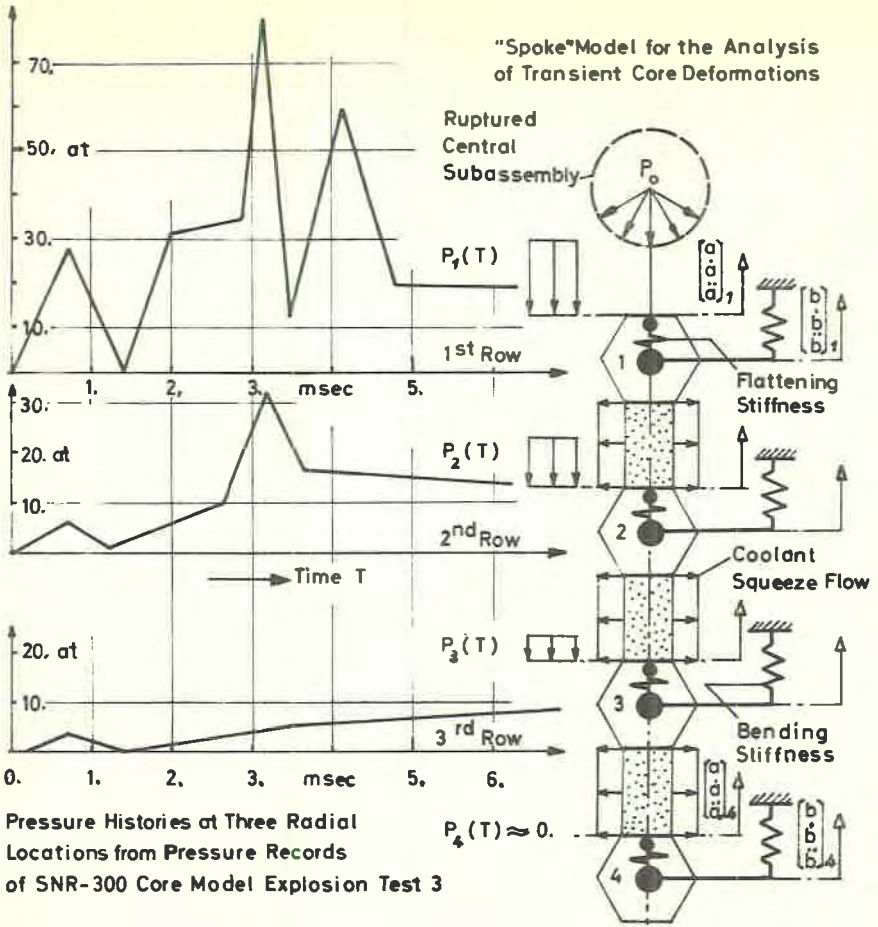
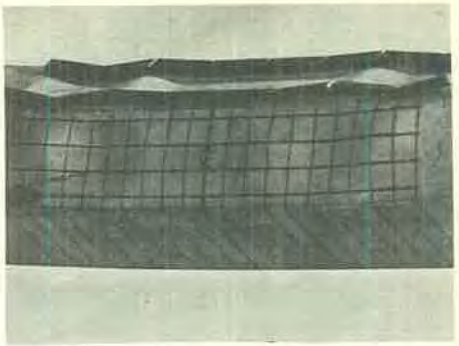


Fig. 4 Constitutive Law and Numerical Results of a Nonlinear Transient Response Analysis



Pressure Histories at Three Radial Locations from Pressure Records of SNR-300 Core Model Explosion Test 3

Fig. 5 Pressures from Core Model Explosion Tests and Analytical Model for Multirow Core Calculations



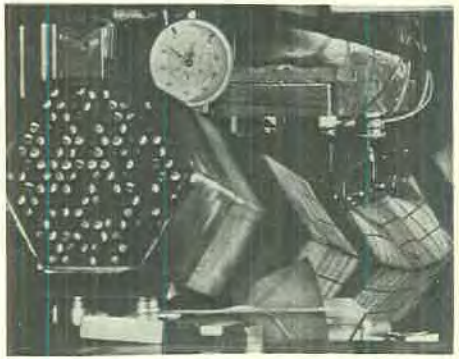


Fig. 6 Static and Impulsive Experiments on Single Fuel Elements

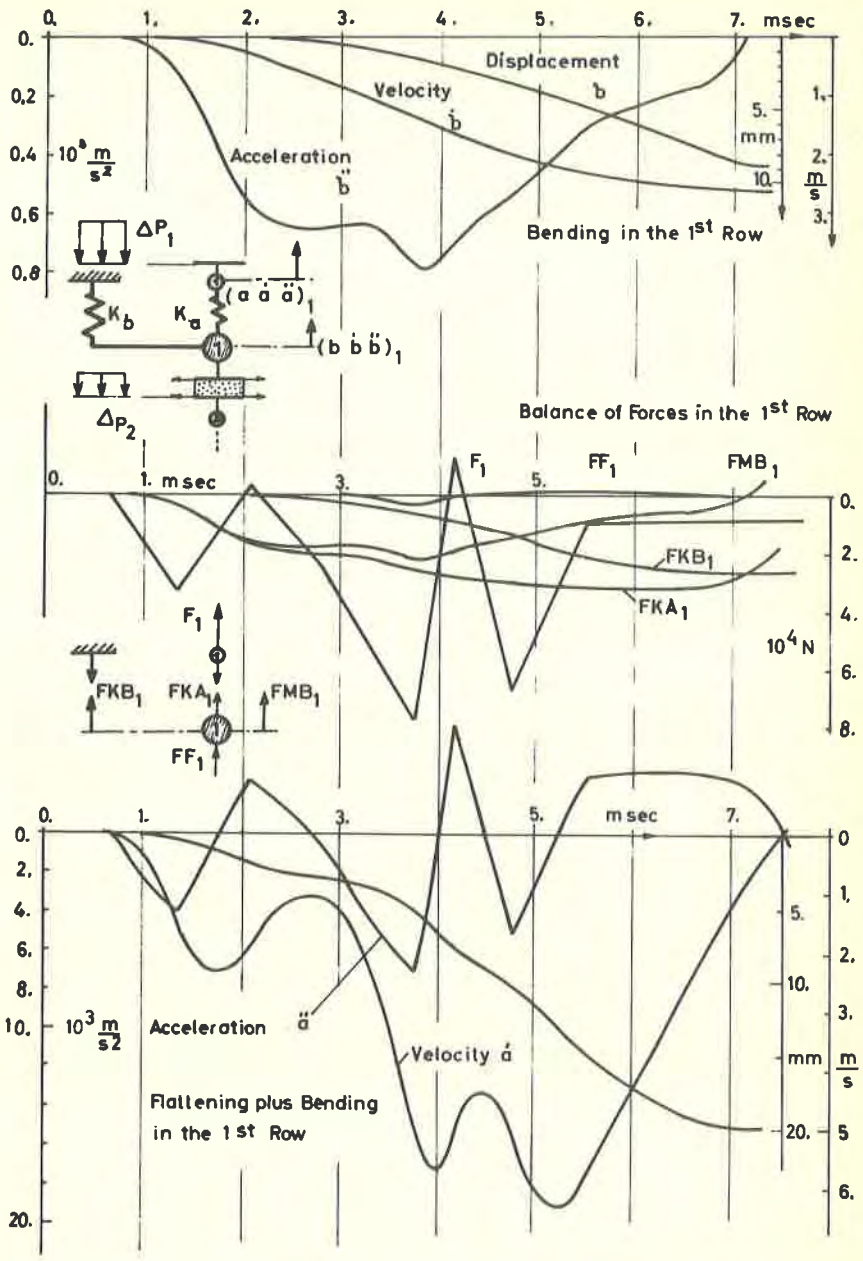


Fig. 7 Numerical Results of SNR-300 Transient Response Analysis Using Input from Fig. 5