E 2/1*

MECHANICAL BEHAVIOR OF THE LMFBR CORE STRUCTURE UNDER TRANSIENT PRESSURE DUE TO LOCAL FAILURE

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SUMMARY

In fast reactor safety analysis the structural integrity of the reactor core in case of any local failure has to be demonstrated. Such local events may be due to random pin failure which is very likely. As a consequence contact between molten fuel and coolant may occur. The existing uncertainties in the understanding of the physical mechanisms observed during this molten fuel-coolant-interaction (MFCI) emphasize the importance of the comprehensiveness of this research program.

This paper describes the effort done at GfK Karlsruhe to predict the core deformations caused by local failure within an LMFBR core. These activities try to cover all important questions currently discussed in the analysis of possible core damage. Particularly it is shown that the reactor can be scrammed in time under pessimistic-realistic pressure transients and that the damage does not exceed tolerable limits.

The software for the general simulation of the deformation history utilizes numerical methods for discrete models of various levels of refinement. The theoretical investigation distinguishes models concerning the pin-to-pin failure propagation, the subassembly deformation and the structure-coolant interaction. Detailed studies of the local events using a singularity method do not exclude subassembly-to-subassembly failure propagation. Therefore, the elasto-plastic dynamic behavior of a flattening and bending hexcan being externally loaded and filled with coolant and a pin-bundle is thoroughly analyzed. The damage propagation and energy dispersion between adjacent ducts is affected by the expulsion of the coolant within the hexcans and by the cushioning effect of the fluid layer squeezed out of the gaps between them.

Split-Hopkinson-bar tests performed in cooperation with EURATOM deliver the wrapper material properties.

Underwater explosion experiments on full-scale models for the SNR 300 core are performed in collaboration with UKAEA employing a gas-generator technique. The extensive instrumentation yields realistic pressure-time-histories as well as deformation measurements.

For code validation a series of static and impact experiments on single subassemblies is performed using a drop tower.

A 3D-analysis of the MFCI-induced fluid expansion within a two row pin-bundle delivered pin bending (0.25%) and ovalization strain (2%). The results show that pin-to-pin failure propagation cannot be ruled out completely. Therefore, the results of the subassembly deformation analysis become important.

For the whole core analysis only preliminary computational results are presently available for comparison with full-scale tests, where the fluid pressure did not exceed a "threshold" of about 100 bar. Permanent subassembly deformations are not necessarily concentrated at the fuel element next to the "incident" wrapper. Parameter studies show the influence of pulse shape, time integrator, and material properties. The use of shock- and damage-diagrams condenses general numerical results.

Some of the open questions concern the hydrodynamic feedback of the deformations on the pressure distribution in space and time. The behavior of highly irradiation-embrittled cores is poorly understood today. Finally, an enhanced energy release package must still be added to the reactivity calculation module of a future fast reactor dynamics code.

1. Introduction

A satisfactory fast reactor safety analysis requires a comprehensive experimental and theoretical research program. The structural integrity of the reactor core in case of any local failure has to be demonstrated. Such local events may be due to random pin failure which is very likely. As a consequence contact between molten fuel and coolant may occur. The existing uncertainties in the understanding of the physical mechanisms observed during this molten fuel-coolant-interaction (MFCI) emphasize the importance of the comprehensiveness of this research program.

This paper describes the effort done at GfK Karlsruhe in cooperation with UKAEA and EURATOM to predict the core deformations caused by local failure within an LMFBR core. These activities try to cover all important questions currently discussed in the analysis of possible core damage. It may be concluded that the reactor can be scrammed in time under pessimistic-realistic pressure transients and that the deformations do not exceed tolerable limits. The computer methods are general enough as to allow for different core designs with varying geometries, material properties, etc.

2. Research Program

The theoretical investigation of core response under transient pressure loads distinguishes models concerning the pin-to-pin failure propagation, the structure-coolant interaction and the subassembly deformation. The possible causes and consequences of impulsive loads acting on the core structure must be compared with the results of an experimental program to demonstrate the evidence of safety for any particular LMFBR. The reasoning behind this demonstration is shown in Fig. 1.

The experimental effort includes experiments on the MFCI, explosion tests on full-scale core models and impulsive tests with single subassemblies as well as reactor steel specimens.

Fig. 1 shows that two different "entries" to the evidence of safety exist. "Direct" evidence is accepted, if the maximum experimental pressure history ($p_{Ex}(t)_{max}$), which could not yet produce intolerable damages during a full-scale explosion test lies always above a pessimistic realistic MFCI pressure history $p_{FCI}(t)_{max}$. Whenever this is not the case, a comparison has to be made between these worst case MFCI results and the maximum pressure $p_o(t)_{max}$ from the overstrong wrapper tests performed to calibrate the gas generator prior to those explosion tests. Theoretical analysis can help to confirm the evidence of safety in case the FCI pressures always exceed the wrapper pressures (both taken in the same confinement geometry). We tend to call this approach the "indirect" evidence of safety.

Regarding the many uncertainties still existing in the present knowledge about the MFCI [1], pessimistic-realistic experiments studying the fragmentation of the molten-fuel (Fig. 2) are mandatory [2]. At present, local pin-to-pin failure propagation due to pressure pulses caused by random pin failure within a disturbed region of slightly elevated temperature cannot be ruled out completely. Dropping experiments with UO_2 and sodium recommended a fluid source rate of $8 \cdot 10^8$ cm^3/sec^2 leading to a maximum pin bending strain of about 0.25 % and a maximum ovalization strain of about 2 % (Fig. 3). This strain changes sign through the can wall. Therefore, despite the higher strain value for ovalization, the bending strain presents a critical result. Taken together both strains seem to reach the lower bound of some ultimate strains measured for highly irradiated cladding material.

The results presented in Fig. 3 have been computed with a special singularity method [3] for yielding the 3D, transient solution of the coupled fluid-structure mechanics. The MFCI is simulated by a fluid source located at the center of a two-row pin bundle. The coolant is assumed to be incompressible and inviscid. The distribution of sources, dipoles and quadrupoles along the pin axis generates the fluid motion due to pin dicplacement. Of course, these distributions have to be determined iteratively to yield force equilibrium between fluid and pin.

As the uncertainties in the pressure pulse and, consequently, the likelihood of pin-to-pin failure propagation cannot be reduced significantly, there exists a potential for subassembly-to-subassembly failure propagation [4]. The sudden expansion of a failing hexcan may produce an impulsive load deforming the adjacent ducts plastically. The software for the general simulation of the deformation history of a single subassembly utilizes numerical methods for discrete models of various levels of refinement. In particular, the elastoplastic dynamic behaviour of a flattening and bending hexcan (Fig. 4) being externally loaded and filled with coolant and a pin-bundle is thoroughly investigated [5]. It accounts also for the structure-coolant interaction (Fig. 5) by an incompressible squeeze flow model including friction.

Simple mass-spring-dashpot models were coupled with this nonstationary fluid package and extended to simulate an array of subassemblies. Fig. 8 shows typical results of a transient core deformation analysis directly utilizing experimental force-deflection characteristics. More refined structural models for the analysis of cross section flattening are based on nodal discretizations with concentrated bending moments and elastoplastic hinges (see companion paper E 2/3 of this conference). A 4th-order variable step Runge-Kutta integrator was found to be suitable for the solution of the resulting set of nonlinear differential equations.

Complementary work on the hexcan bending mode currently assesses various Timoshenko beam discretizations including shear and rotatory inertia. Numerical peculiarities of such models provoke comparative studies of the accuracy, efficiency and stability of appropriate time integrators. Our preliminary conclusion from this effort is to recommend the implementation of an explicit scheme utilizing a 4th order Taylor operator (see companion paper E 2/2 of this conference) [9].

The comprehensiveness of the research program is achieved by backing up the theoretical analysis by an extensive experimental program [2, 6, 7] which consists of 4 parts:

1) MFCI-tests utilize a tungsten crucible filled with molten UO_2. When falling on a sodium injector needle penetrating through its bottom, the crucible triggers the pre-fragmentation of the molten fuel (Fig. 2).
2) Split-Hopkinson-bar tests deliver the wrapper material properties (stress-strainrate-laws).

Both activities are performed in cooperation with EURATOM (Ispra, Italy).

3) Underwater explosion experiments on full-scale models of the SNR 300-core are performed in collaboration with UKAEA (AWRE Foulness) employing a gas generator technique to simulate the desired pressure loading by a chemical propellant. The extensive instrumentation measures pressure-time histories as well as deformations /¯7_7.
4) For code validation a series of static and impact experiments on single subassemblies was performed using a drop tower designed and installed at Karlsruhe (Fig. 6).

Honeycomb crushing material allows for both force and motion control according to desired pulse requirements. The purpose of these experiments on force-deflection characteristics, energy absorption capabilities and time scales of subassembly deformation is to support several hypotheses and to prove the relative significance of hexcan, bundle and coolant interaction. In addition the experimental data help to understand and generalize the findings of full-scale explosion tests on SNR-300 core models /¯7_7.

In this test series the gas generator charge located inside the "incident" subassembly of the core model was gradually increased to reach an upper limit of tolerable damage during the first four shots. In these tests the hexcan materials and dimensions were chosen to represent the strength of a mildly embrittled steel whereas in the fifth shot the fresh state of the core was simulated.

3. Results and preliminary conclusions

Preliminary results of this program demonstrate that control rods remain operable for scram and that reactivity changes due to cavities as well as core deformation under an FCI in a single subassembly do not exceed tolerable limits established by safety requirements. In particular, the extensive instrumentation installed to record almost all essential quantities during the transient deformation yielded important information about the strains within the fuel element mockups and through the restraint zones, about the forces acting on the vessel, the instrument plate and the core internals and about the pressures within the subchannels between and inside the hexcans (Fig. 7). Some difficulties arose due to resonance effects met with the acceleration pickups. Post-test inspection gave a precise picture of the permanent damage (Fig. 7). The typical data describing the first 5 tests are compiled in table I.

A careful interpretation of the explosion tests permits the following preliminary conclusions /¯8_7:

- a peak pressure of about 100 bars at incident wrapper location seems to be a "threshold" which hitherto could not be exceeded even when increasing the propellant charge by a factor of 3 in terms of pressure (see table I). Below this limit no intolerable permanent subassembly deformation was observed
- changing the hexcan material in test 5 did not change the resulting pressures and deformations significantly. From this it may be conjectured that in the pressure regime covered by the experiments the hydraulic properties of the core have the dominant influence on the load distribution and history
- the observed damage was always confined to the first row. To produce damages extending to the next row(s), an unrealistically dramatic increase of the explosive charge is necessary. For sake of completeness and conservativism a further shot aiming to realize such an extension is being performed at time of writing.

Other important experimental results are:

- static loading experiments on empty hexcans confirmed limit load calculations and demonstrated localized yielding as well as the formation of hinges in the corners. Expected nonlinear load-deflection characteristics were obtained which are also due to geometry changes of the hexagon and strain hardening of the material
- static tests on SNR-type subassemblies showed a very large stiffening effect of the pin bundle interacting with the hexcan through the spacer grids.

These observations were successfully cross-checked with theoretical predictions, which are summarized as follows:

- computations were performed on elastoplastic hexcan deformation, plastic work and coolant motion utilizing the outlined models and methods /‾5,6_7
- parameter studies indicated the relative importance of energy absorption by structural deformation and the large influence of hexcan corner ductility on plastic flattening
- large pulse shape effects were observed in most of the cases considered. It is possible, however, to determine generalized damage diagrams when using "equivalent" pulse parameters /‾5_7.

A transient analysis of core response with input from measured pressure histories yielded the forces, deflections and velocities within a 4 row spoke model (Fig. 8), which decay rapidly in the radial direction. Fig. 7 allows the cross-checking of the spatial pressure distribution as well as the permanent deformations which agreed reasonably well.

Some of the open questions concern the hydrodynamic feedback of the deformations on the pressure distribution in space and time. The behaviour of highly irradiation-embrittled cores is poorly understood today. Finally, an enhanced energy release package must still be added to the reactivity calculation module of a future fast reactor dynamics code.

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The investigation is being performed at GfK, Karlsruhe under the auspices of the German Federal Fast Breeder Reactor project. The investigation of pin-to-pin failure propagation was performed on visit at Argonne Natl. Lab., Chicago, USA.

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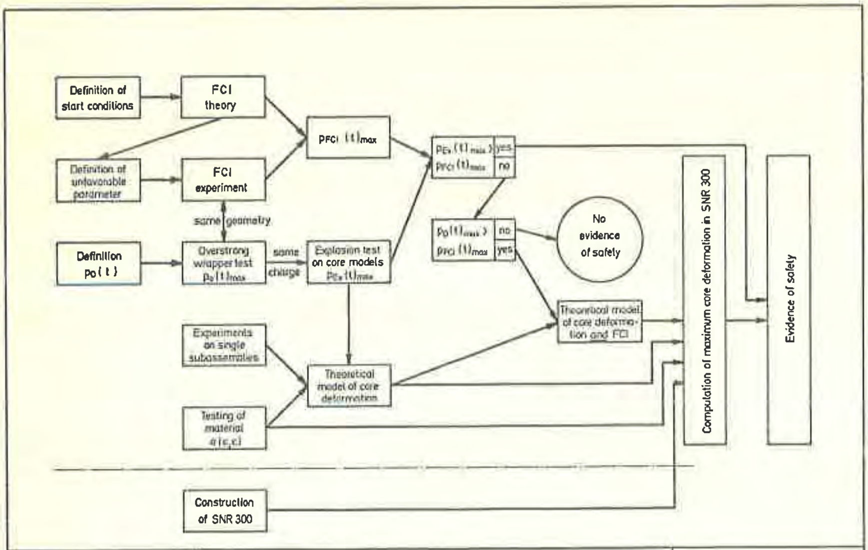
Table I: <u>Important parameters of the explosion test program</u>

Tests 1 to 4: Heat treated St 45 to simulate a 4981 steel having experienced a fluence of 10^{22} nvt. Only the peak pressure was varied.

Test 5: Austenitic steel 1.4306 with reduced wall thickness to simulate fresh 4981 steel. Same charge as in test 3.

Test No.	Overstrong Wrapper Test				Whole Core Model Test			
	peak pressure wrapper kp/cm^2	peak pressure gas gen. kp/cm^2	rise time msec	half period msec	peak pressure core kp/cm^2	peak pressure gas gen. kp/cm^2	rise time msec	half period msec
1	125	250	4	15	35	310	3	3
2	250	520	3.5	22	95	480	5	10
3	380	830	3	13	104	800	4.5	5.5
4	720	1510	3	13	105	1450	2.5	4
5	380	830	3	13	105	880	4	4



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Logic to evidence of safety

Fig. 1

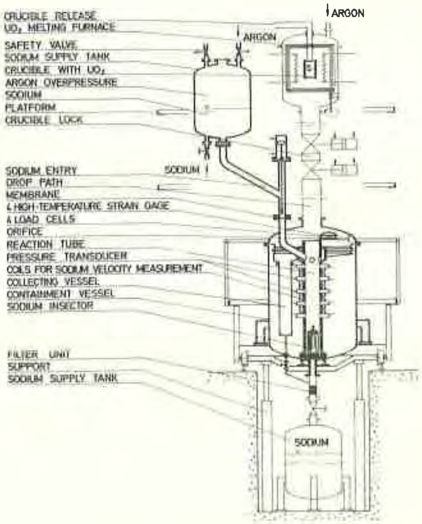


Fig.2: Experimental Equipment for the Investigations on Molten Fuel-Coolant Interactions with Pre-Fragmentation

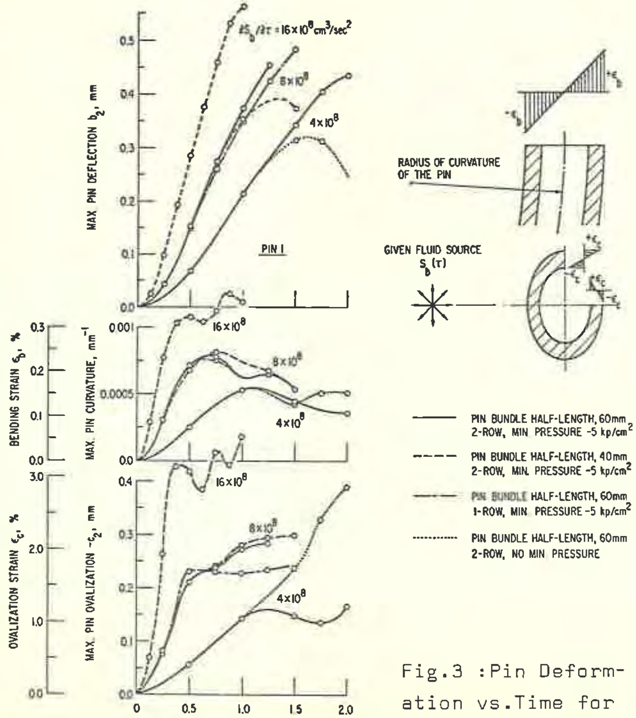


Fig.3 :Pin Deformation vs.Time for 3 Different Source Rates

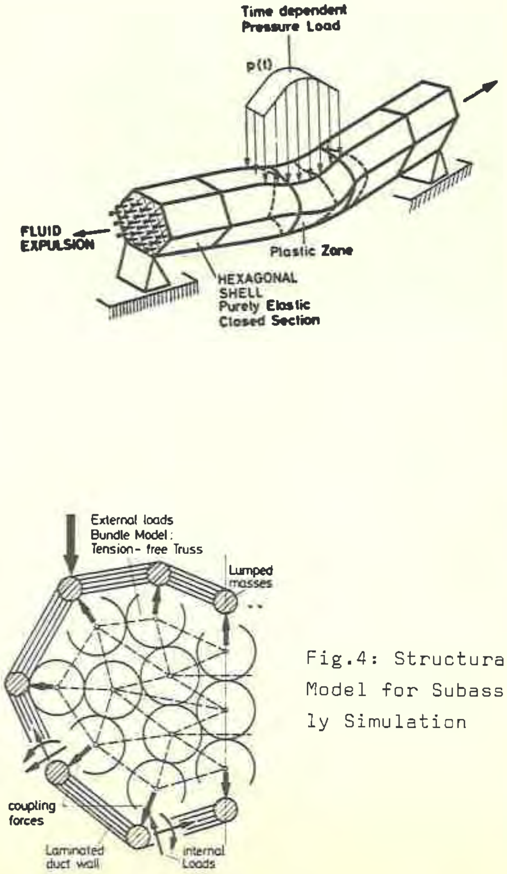
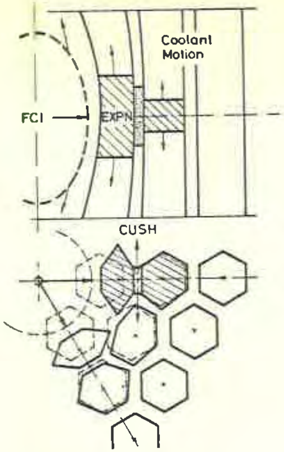
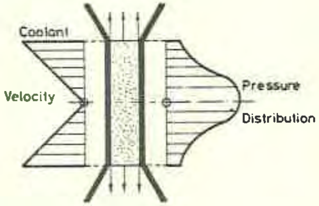


Fig.4: Structural Model for Subassembly Simulation

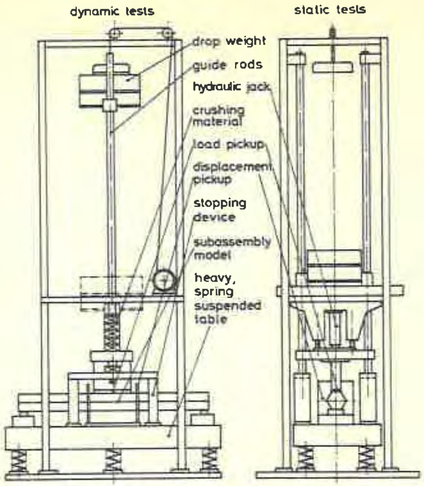


a) Principal Effects



b)Squeezing Model

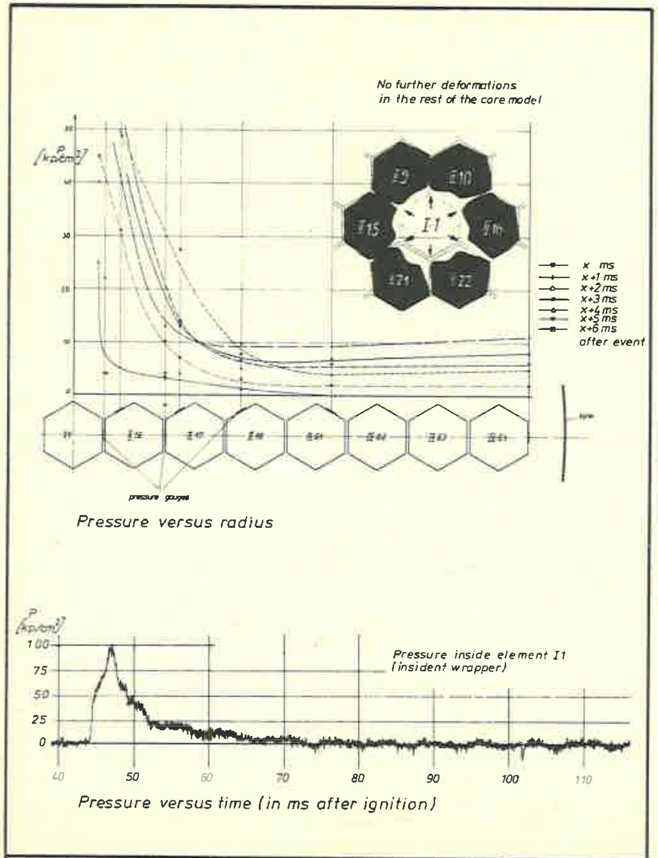
Fig.5: Core Structure-Fluid Interaction Including Vapor Bubble Growth (FCI), Coolant Expulsion (EXPN) and Cushioning Effect (CUSH)



a) Drop Tower

b) Deformed Hexcan

Fig.6: Impact Test Facility



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Pressure distribution, Pressure history and Deformation pattern

Fig. 7

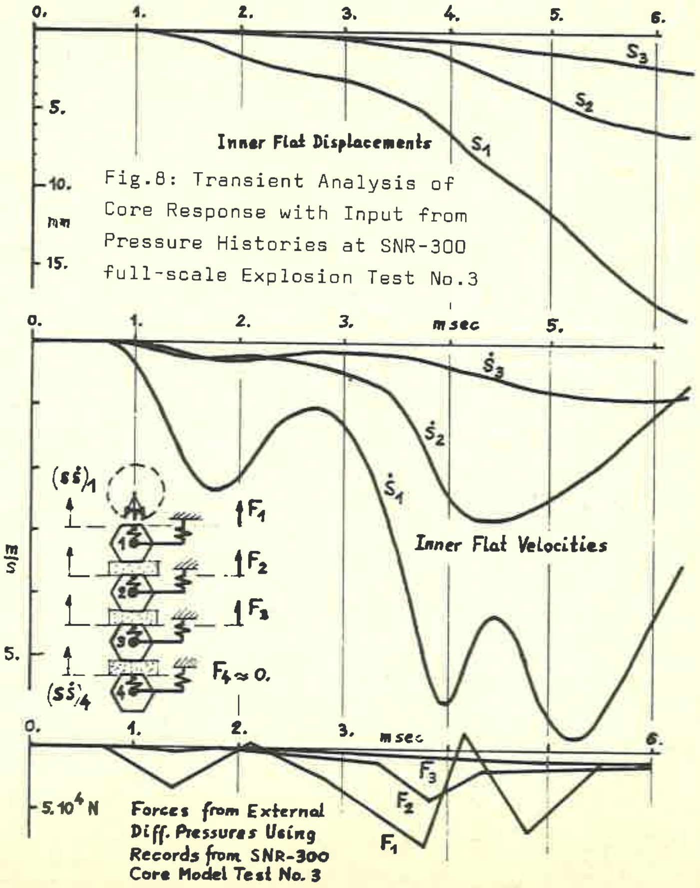

Fig.8: Transient Analysis of Core Response with Input from Pressure Histories at SNR-300 full-scale Explosion Test No.3