

## Fluid-Structure Interaction Effects for an FFTF Experiment

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### SUMMARY

The STRAW code was used to analyze the static and dynamic response of a proposed FFTF multi-hexcan test vehicle under quasi-static and transient internal pressures for the purpose of assessing its strength and deformations. STRAW is a program for transient analysis of fluid-structure interaction problems with both material and geometric nonlinearities.

In this test a cluster of 37 carbide fuel pins will be irradiated. The carbide pins will be surrounded by two rows of standard oxide fuel pins; the two types of pins will be separated by two concentric thin wall hexagonal cans, and the entire configuration will be enclosed by a standard FFTF size outer hexagonal can. If it is postulated that the inner zone of pins undergoes an accident sequence such that a pressure pulse is generated, then prevention of mechanical damage to the oxide pins depends on the strength of the two inner hexcans. For these reasons, the prediction of the deformation and strength of the three hexagonal cans is of importance in the planning of an experiment.

The analysis was subdivided into three tasks: (1) a quasi-static analysis of the complete assembly including the fluid between the concentric hexcan wrappers for determining the static failure load; (2) a series of transient analyses of the complete assembly to determine the variation of failure pressure with rise-time; (3) quasi-static analyses of the individual hexcans to determine the failure pressure if they should become uncoupled. The last task is of pertinence in determining the response of the system if one of the inner hexcans should fail.

The analyses show that the quasi-static capacity of the hexcan assembly is 8.27 MPa (1200 psi), if the failure criterion is taken to be 8% strain. This is substantially above the capacity of the individual hexcans which are 6.07 MPa (880 psi), 1.96 MPa (285 psi), and 2.68 MPa (388 psi) respectively from outside to inside. With a rise time of 0.1 milliseconds the dynamic capacity of the complete assembly is about 6.55 MPa (950 psi), while for such dynamic loads the capacity of the individual cans is substantially less, the use of a model that accounts for fluid-structure interaction was able to indicate substantial reserves in strength.

## 1. Introduction

This analysis pertains to the experiment (ACN-1) proposed for the Fast Flux Test Facility (FFTF) in which a cluster of 37 carbide fuel pins will be irradiated. The carbide pins will be surrounded by two rows of standard oxide fuel pins; the two types of pins will be separated by two concentric thin-wall bed hexagonal cans, and the entire configuration will be enclosed by a standard FFTF outer hexagonal can. This arrangement of the three concentric hexcans is shown in Fig. 1.

If it is postulated that the inner zone of pins undergoes an accident sequence such that a pressure pulse is generated, then prevention of mechanical damage to the oxide pins depends on the strength of the two inner hexcans. Similarly, prevention of mechanical damage to adjacent subassemblies depends on the response of the outer hexagonal can. For these reasons, the prediction of the deformation and strength of the three hexagonal cans is of importance in the planning of the experiment.

This study was undertaken with the ANL/RAS computer code STRAW. The STRAW [1] program was developed for the analysis of subassemblies in the Liquid Metal Fast Breeder Reactor.

It treats the transient response of fluid-structure systems with both material and geometric nonlinearities. Calculations by the STRAW code were recently compared with experiments performed at the Stanford Research Institute (SRI) for a subassembly cluster test [2]. Good correlations were achieved between the code calculations and the data for these hexcan tests, demonstrating that the STRAW code is an appropriate tool for this type of analysis. Because of uncertainties in source strengths at the subassembly level, the STRAW code was designed to handle a large range of pressures and time scales.

This paper reports the results obtained with the STRAW code in the safety assessment of the test vehicle. The purpose of this analytical study was to determine the ability of the multi-hexcan test vehicle to withstand both static and transient internal pressures and to study the role of fluid-structure coupling in the response.

A series of pressure time histories ranging from very impulsive loads to those with durations comparable to the period of the lowest frequency of the structure, a particular hypothetical pressure time history, and quasi-static loadings were considered.

We first describe the models chosen for the multi-hexcan vehicle. Next, results are presented for static and dynamic loadings; the loads subjected to the hexcans individually without fluid coupling and with a model of the fluid, which enables them to act together.

## 2. Finite Element Models

The cross-section of the vehicle is shown in Fig. 1. A two-dimensional, plane-strain model of the cross-section was chosen for the analysis. The two-dimensional analysis is justified because the pressure is applied axially over a length of several diameters of the hexcan; thus, the bending response normal to the cross-section is negligible compared with bending in the cross-section. The pressure was applied to the inner wall of the innermost hexcan. The loading is assumed rotationally symmetric in all cases; thus symmetry was exploited to reduce size of the model to 1/12th (the 12-fold symmetry is indicated in Fig.

1). The hexcan walls are represented by beam elements; the sodium by quasi-Eulerian quadrilateral hydrodynamic elements. Sliding interfaces were used between the fluid and hexcan walls. A total of 208 elements was used in the model: 16 beam elements for the half-flat of each hexcan, and 160 hydrodynamic elements. In addition, a coarse mesh with 88 elements was also used in these studies.

The hexcan walls were stainless steel. They were treated as elastic-plastic with material properties given in Table 1. The sodium was treated as inviscid, compressible with a constant bulk modulus, as given in Table 1.

The equations of motion were integrated by the explicit, central-difference method. Time steps of 0.1  $\mu$ s to 0.2  $\mu$ s were used, so 10,000 to 5,000 time steps were required per millisecond of simulation.

### 3. Quasi-static Strength of Individual Hexcans

Each of the hexcans was first analyzed individually by applying a linearly rising pressure load to its inside wall to determine its static capacity. Failure was here defined to be 8% strain, which, in all cases, was first reached at the corner. The results are summarized in Table 2. It should be noted that the inner hexcan alone can withstand only about 2.41 MPa (350 psi) according to this criterion.

The strain distribution of the inner hexcan (C) for a load of 2.41 MPa (350 psi) at the outside and inside surfaces plus the membrane value is given in Fig. 2. It can be seen that the major component of the response is bending, for the strains on the inside and outside walls are nearly equal in magnitude but opposite in sign. This is supported by the negligible value for the membrane strain.

From the results in Table 2, it can be seen that the center hexcan (B) is the weakest of the three, which is partially due to the small radius of the fillet in its corners. The outermost hexcan (A) is the strongest because of the large thickness of its walls.

### 4. Quasi-static Strength of the System

The quasi-static strength of the system was determined by loading it to 8.27 MPa (1200 psi) in 1.5 ms. The longest natural period of the system is about 0.5 ms, so this rate of loading was sufficiently low to preclude any significant dynamic effects. The results were obtained for both the fine and coarse mesh and are also given in Table 2 (the difference between the fine and coarse meshes is again about 10%). The strength of the total system is about 8.27 MPa (1200 psi) which is significantly greater than any of the components. The innermost hexcan fails first but the failure pressure is more than three times greater than that for the isolated hexcan.

It is of interest to observe the strain as a function of load for the points of maximum strain in the three hexcans, as shown in Fig. 3. The strain associated with plastic yielding here is 0.003, which is reached at less than 2 MPa (290 psi). This is less than 25% of the static capacity of the system based on a failure criterion of 8% strain. With a strictly linear analysis, this additional strength could not be predicted.

## 5. Dynamic Response of System

In order to ascertain the dynamic behavior of this system, a series of transient analyses were made. The results are summarized in Table 3.

The following observations are made:

1. For a pressure-time history with the rise-time 0.1 msec and duration of 1.0 msec, the dynamic strains for 8.27 MPa (1200 psi) maximum pressure are almost 50% greater than for the quasi-static response; therefore, for this  $p(t)$ , the dynamic capacity is less than the static capacity.
2. The maximum strains diminish substantially with increasing rise-time until the rise time is about 0.5 ms (the natural period of the system).
3. In all cases, the innermost hexcan experiences the largest strains.

The nature of the response is elucidated by comparing the strain-time histories for the corner of hexcan C for a 8.27 MPa (1200 psi) peak with 0.1 ms and 0.3 ms rise-times. In both cases the maximum strain is attained in about 0.4 ms; subsequently the strain oscillates elastically about its permanent strain. However, for the quicker rise-time, a higher strain is attained. The duration of the load after the peak for this magnitude of pressure appears to have little bearing. However, for the largest pressures, as shown previously, the strain continues to increase as long as the pressure is applied.

The last run in Table 3 is a pressure associated with a target loading. For this pressure, substantial strains are developed. The final deformed shape of the finite element model is shown in Fig. 4. As can be seen, the hexcans become almost circular in cross-section; this entails considerable bending at the corners, which are in all cases the points of maximum strain.

### Acknowledgement

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### References

- [1] Kennedy, J. M., "Nonlinear Dynamic Response of Reactor-Core Subassemblies," Argonne National Laboratory Report ANL-8065, January, 1974).
- [2] Romander, C. M., Cagliostro, D. J., "Experiments on the Response of Hexagon Subassembly Duct Clusters to Central Radial Loads," SRI Report, December, 1976.

Table 1. Material Properties for FFTF Test Vehicle Study

Stainless Steel at 593°C (1100°F)	
Density	$\rho = 7.73 \text{ g/cm}^3 (7.228 \times 10^{-4} \text{ lb-s}^2/\text{in}^4)$
Poisson's Ratio	$\nu = 0.30$
Yield-Stress	$\sigma_y = 4.62 \times 10^9 \text{ dynes/cm}^2 (6.70 \times 10^4 \text{ psi})$
Young's Modulus	$E = 1.54 \times 10^{12} \text{ dynes/cm}^2 (2.23 \times 10^7 \text{ psi})$
Yield-Strain	$\epsilon_1 = 0.0030$
Ultimate Strain	$\epsilon_2 = 0.0800$
Ultimate Stress	$\sigma_2 = 5.10 \times 10^9 \text{ dynes/cm}^2 (7.40 \times 10^4 \text{ psi})$
Liquid Sodium at 593°C (1100°F)	
Density	$\rho = 0.85 \text{ g/cm}^3 (7.944 \times 10^{-5} \text{ lb-s}^2/\text{in}^4)$
Bulk-Modulus	$B = 4.00 \times 10^{10} \text{ dynes/cm}^2 (5.80 \times 10^5 \text{ psi})$

Table 2. Static Failure Pressures  
(Failure defined as 8% strain)

	No. of Nodes	No. of Elements	Failure Pressure	
			MPa	(psi)
Hexcan A	17	16	6.07	(880)
Hexcan B	17	16	1.96	(284)
Hexcan C	18	8	2.68	(388)
Hexcan C	34	16	2.39	(346)
Complete couple fluid-structure system	108	88	9.24	(1340)
Complete couple fluid-structure system	238	208	8.27	(1200)

Table 3. Dynamic Results, Coarse Mesh, 108 Nodes, 88 Elements

Run	Peak Pressure, $P_0$ MPa (psf)	Rise Time, $t_1$ ms	Pulse Width, $t_2$ ms	Maximum Tensile Strain, HEXCAN C	Maximum Tensile Strain, HEXCAN B	Maximum Tensile Strain, HEXCAN A
1	6.89 (1000)	0.1	1.0	0.087	0.057	0.049
2	5.52 (800)	0.1	1.0	0.047	0.031	0.028
3	8.27 (1200)	0.1	1.0	0.128	0.086	0.067
4	8.27 (1200)	0.2	1.0	0.112	0.072	0.059
5	8.27 (1200)	0.3	1.0	0.085	0.057	0.048
6	8.27 (1200)	0.5	1.3	0.077	0.052	0.044
7	8.27 (1200)	0.75	1.55	0.072	0.049	0.041
8	7.58 (1100)	0.2	1.0	0.089	0.059	0.050
9	13.79 (2000)	0.2	1.0	0.200	0.125	0.091
10	13.79 (2000)	0.4	1.0	0.168	0.123	0.084
11	13.79 (2000)	0.6	1.0	0.155	0.111	0.080
12	13.79 (2000)	0.8	1.0	0.150	0.107	0.078
13	13.79 (2000)	1.0	1.0	0.131	0.091	0.070
14	11.03 (1600)	0.5	1.0	0.131	0.091	0.070
15	11.03 (1600)	1.0	1.0	0.110	0.074	0.059
16	34.47 (5000)	0.1	1.0	0.284	0.258	0.341

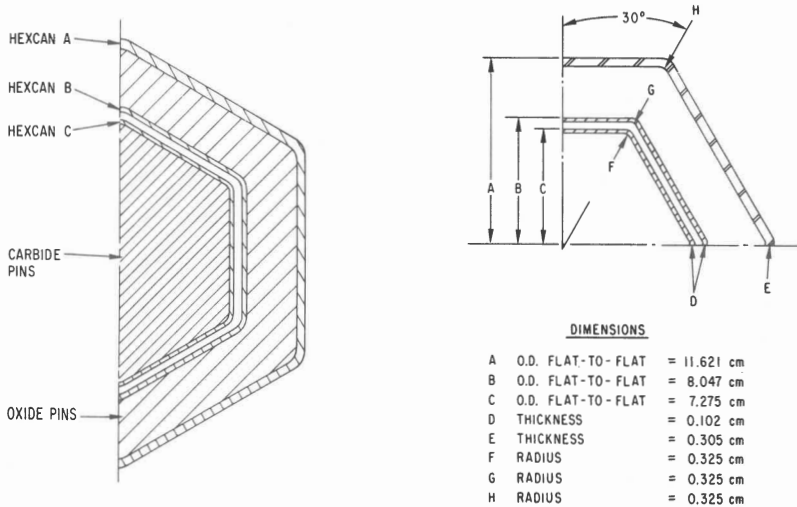
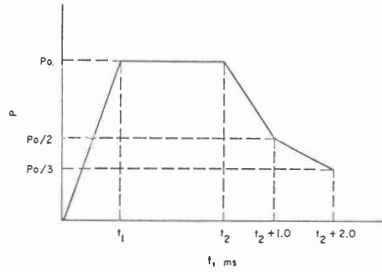


Fig. 1. The ACN-1 cross section showing oxide and carbide pins.

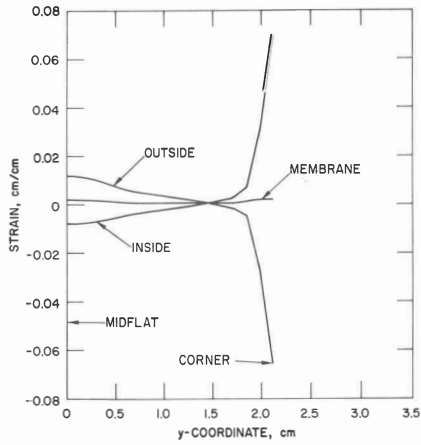


Fig. 2. Strain distribution for Hexcan C (innermost hexcan).

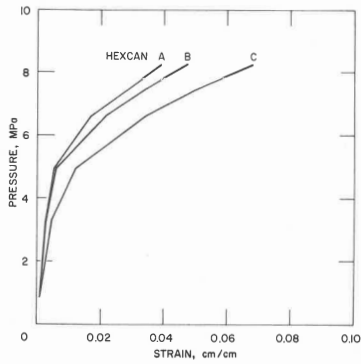


Fig. 3. Hexcan strains as a function of pressure.

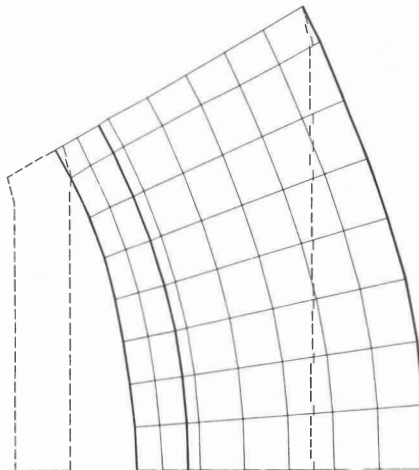


Fig. 4. Deformed configuration at 1.2 ms -- 34.5 MPa loading.