AN EMPIRICAL STUDY OF THE EFFECTS OF A SIMULATED SODIUM COOLANT VAPOUR EXPLOSION IN A SUB-ASSEMBLY OF THE PFR CORE STRUCTURE

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SUMMARY

A full scale model of the PFR core, containing 61 sub-assemblies and control rod guide tubes, surrounded by concrete blocks to simulate the inertia of the remainder of the core, is described. The model was subjected to the damaging effects of a propellant explosion designed to simulate the pressure-time pulse which is expected to be produced by a fuel-coolant thermal interaction vapour explosion. The propellant is burnt inside a strong walled tube with vent holes in the wall designed to deliver high pressure gaseous combustion products to the incident sub-assembly to produce the required pressure pulse. A separate paper describes this system.

The sub-assemblies were manufactured from a mild steel having similar mechanical properties at atmospheric temperatures to stainless steel at reactor operating temperature. Each sub-assembly was filled with mild steel rods to simulate fuel pins. An attempt to investigate the crushing effect on fuel pins weakened by overheating was made by replacing a few of the dummy fuel pins with perspex tubes filled with lead shot.

The sub-assemblies were supported on a base plate but not spigoted into it. To supply the radial elastic restraint which sub-assemblies cantilevered at their base spigots would normally possess, a number of rings of tensile springs were assembled around the outside face of the concrete blocks.

The model was submerged in water in a tank 7 m deep to simulate the head of sodium coolant in the reactor.

The outward movement of the concrete blocks was recorded by deflection transducers during the test. The transient pressure pulse produced by the propellant in the sub-assembly was recorded with quartz piezo-electronic pressure transducers. Also the pressure in the water 30 cm outside the core boundary was measured.

Any distortions in the sub-assemblies were recorded after the test by drawing the profiles of each assembly at a series of cross sections along its length. A profile drawing machine was specially designed and constructed for this purpose.

The results of this test are compared with earlier work in which similar models were tested with high explosive charges. Although such charges produce a pressure pulse which is very much shorter than the duration expected of a vapour explosion it is shown that there is little difference in the damage effects.

1 Introduction

A first attempt was made in 1966 to estimate the damage which might be caused in a typical Fast Reactor core by a "SPERT" type vapour explosion in a single sub-assembly. It was thought that an upper limit to the damage could be obtained by using high explosive. A low brisance explosive (Quarrex) was used in a model experiment [1]; the pressure pulse at the wrapper wall had a peak value 4 times greater and a duration 100 times shorter than the pressure pulse that had been estimated for a vapour explosion. If the damage had been slight in these initial tests, then the integrity of a core of this type to a real incident would have been assured and no further tests would have been required. In fact the damage was considerable and confirmed the need for the current series of tests started in 1972 using a more realistic simulation of the "SPERT" incident. The first experiment used 19 sub-assemblies and control-rod guide tubes inside concrete inertia blocks; this was primarily an instrumentation proving experiment [2]. The second experiment, described here, used 61 sub-assemblies and control-rod guide tubes inside the inertia blocks.

2. Simulation of a Sodium Vapour Explosion

In water cooled reactors there has only been one recorded "SPERT" vapour explosion; in sodium cooled fast reactors no explosions have been recorded. Therefore very little information is available about the (pressure, time) characteristics of, and energy released by vapour explosions, and some estimation of likely values for these parameters has to be made.

2.1 The Energy Release

Teague [3] has calculated that the maximum mechanical energy available using the sodium vapour as the working fluid would be about 20 MJ; he assumed that only one sub-assembly of similar size to the UK type used in PFR was involved and that the thermodynamic maximum quantity of energy was available from the heat stored in the UO_2. In practice it is expected that the energy developed will fall considerably below the thermodynamic limit, and that it is incredible that all the fuel in a sub-assembly should become molten and produce a single interaction involving all this fuel simultaneously. It was therefore decided that an energy availability of about 4 to 6 MJ was an appropriate level at which to start an assessment of the damage that may be produced in the reactor core by the vapourised sodium coolant.

2.2 The Pressure Pulse Produced by the Thermal Interaction

The pressure produced by sodium vapour inside a sub-assembly will depend on the balance between the rate at which vapour is formed and the rate at which it can expand. The former will be determined by the fuel/coolant interaction conditions and the latter, firstly by the geometry of the coolant flow channels in the wrapper at the time of the incident, and secondly by the way in which the sub-assembly fails and vents the vapour produced. It has been assumed that the most likely precursor to a major incident would be complete flow blockage at the bottom end of the wrapper, followed by a partial fuel melt down, with a 50% blockage at the top end. For the purpose of calculating the subsequent vapour pressure build-up, it is assumed these precursor conditions remain unchanged during the incident. In reality, it is likely that the 50% blockage will rapidly increase and the wrapper be split open by the sodium pressure.

Teague [3] has considered the problem and although, as he points out, it is unlikely that a fast reactor "SPERT" explosion is a unique event capable of precise definition, we can define the characteristics of a vapour explosion which would fall within the range of credibility. As more information about fuel-coolant interactions becomes available it may be possible to reduce this range, and model core tests may identify a range of events where the damage is tolerable.

The present series of tests utilise the pressure pulse proposed by Teague. This has a peak of 70 MN/m^2 (10,000 psi) with a rise time of not more than 3 ms and preferably 1 ms or less. The pressure is to be maintained above the half peak level for at least 10 ms in an overstrong sub-assembly blocked at the lower end and with 50% of the free-flow area available as a fixed vent at the upper end.

3 Simulation of a "SPERT" Vapour Explosion

In a separate paper [4], Warren describes the work done to find a reliable method of producing a long duration pressure pulse to simulate the high pressure sodium vapour. A propellant is burned under controlled conditions inside a strong, thick-walled tube with a number of small vent holes drilled in the wall. This tube is mounted inside the incident sub-assembly, as shown in Figures 1, 2 and 3. The pressure in the sub-assembly depends on the rate at which the gaseous combustion products are supplied through the vent holes and the rate of flow out of the top of the sub-assembly, which is filled with water to simulate the sodium coolant.

The sodium vapour is simulated with a mixture of permanent gases and water vapour, although the fluid dynamics of the two will be different. However, exact simulation is impossible, except in actual reactor conditions. It will probably never be possible to define the precise conditions of a "SPERT" vapour explosion, but the measured pressure loadings we are using and their mechanical effects on the core will be available for later theoretical interpretation when the phenomena are better understood.

3.1 Cordite Charge Burning Tests

The details of cordite and gas generator geometry required to reproduce the pressure pulse defined in 2.2 above, were determined using a mathematical model of the combustion process, with empirical constants. These theoretical results were checked by firing charges in a gas generator inside a dummy overstrong sub-assembly. It must be emphasised that this was a calibration device to ensure that the propellant charge behaves consistently in the manner expected under fixed, known, conditions of volume constraint and venting. In a real sub-assembly which can rupture, the pressure levels produced by the same charge and their duration will be smaller. This will be true also for a sodium vapour explosion.

4 Description of the Experiment

The explosive charge consisted of 0.91 Kg of cordite with 0.5 Kg of gunpowder to give full surface ignition. The model was made of mild steel, to reproduce at ambient temperatures, the properties of the reactor stainless steel at the operating temperature range of 400 - 600°C.

The central incident sub-assembly wrapper was thinned as shown in Figure 4 to simulate the weakness caused by fuel overheating in the incident. The vent holes in the gas generator (Figure 3) were distributed uniformly over the position occupied by fuel section of the pins in the sub-assembly.

The plug at the bottom end of the gas generator was extended outside the sub-assembly to enable the gas generator to be held down to the baseplate of the core model with retractable latches. The bottom section of the incident sub-assembly was also held down by this system but the remainder would be free to eject upwards if the riveted joints failed in the explosion. The possibility of the whole, or part of, the incident sub-assembly and fuel becoming missiles, had to be simulated, but to allow the gas generator to move as well would have been unrealistic. The dummy breeder pins and swirler-mixer at the top end were a simplified design intended to represent the true axial flow resistance. The bottom end of the sub-assembly was completely closed to simulate a blockage incident.

The model of the core (Figures 1 and 2) uses hexagon sub-assemblies of typical fast reactor dimensions, 145 mm across flats and 3 m long but without locating spigots at the lower ends. They contained 325 dummy fuel pins represented by 5.5 mm (7/32 in.) diameter mild steel rods. In some cases these were replaced by simulated crushable fuel pins. These were made of perspex tubing, 3 mm internal diameter and 1 mm wall thickness, filled with lead shot to give an average density of 6.5 g/ml. All the simulated fuel pins were supported by aluminium honeycomb cut to fit the hexagonal wrapper. 400 cells were present of which 19% were left empty to give the correct number fuel pins in each sub-assembly.

The diagrid system was represented by a plain steel plate which provided no location for the lower ends of the sub-assemblies. The control rod guide tubes were clamped to the base plate by a vertical bolt through the plate, threaded into a horizontal bar extending through the walls of the guide tube.

The inertia of the core and the spring-back forces are correctly simulated by the external springs, since the locating spigots at the base of the sub-assemblies were not represented. Successive stages of assembly are shown in Figures 5 and 6.

The experiment was carried out using water to simulate the sodium coolant in the deep tank facility [1].This consists of steel tank 3.9 m diameter, 7.3 m deep with an overhead gantry crane for assembling the models and dissembly afterwards.

A number of transducers were installed in the model to measure:-

(a) Variation of pressure with time both inside the gas generator and between the gas generator and the incident sub-assembly wall.

(b) Variation of pressure with time in the water outside the core.

(c) Transient displacement of the concrete blocks.

(d) Static positions of the concrete stacks before and after the test.

(e) Static measurement of the cross-section of the sub-assemblies and guide tubes, after the experiment.

(f) To obtain records of the sequence of events just above the core, using high speed cine cameras.

(g) Finally by an examination of the model afterwards, an assessment was to be made of the ability of the control rods to continue functioning and the ability of the fuel pins to withstand crushing.

The pressures in the gas producer and wrapper were measured using piezo-electric transducers (type MQ20). One was situated in the centre bolt in the bottom of the gas generator, the others were positioned inside the incident sub-assembly, 210 mm, 965 mm and 1727 mm from the bottom, as shown in Figure 1.

The pressure in the water was measured 305 mm outside concrete block stacks 2, 4 and 6 on a radius through the centre of block β, by tourmaline piezo-electric transducers.

The movement of the stacks were recorded by fixing linear deflection gauges to Blocks α, β and γ of stacks 2, 4 and 6. The height of the gauges from the bottom of the stacks were 406 mm, 1638 mm and 2877 mm. They were supported by a gantry, bolted to the tank wall and floor (Figure 6).

The position of the six stacks was measured, using the angular and radial displacement of the centre and corners of the top block, from the tank centre and wall. This was done before and after the test (Figures 1 and 2; Tables I and II).

The cross-section of the wrappers and guide tubes were obtained by the use of a specially designed rotary measuring machine.

The control rod guide tube positions were marked out on the base plate during assembly of the model before the experiment. Afterwards, the new positions were also marked out during dismantling, to provide a measure of any residual shift suffered by the guide tubes. A dummy control rod of the correct dimensions was positioned inside a guide tube to see if it would be ejected by the coolant if that guide tube deformed under any crushing effect of adjacent sub-assemblies.

High speed cine cameras were used to photograph the top of the model and the bottom of the shroud tube through portholes in the tank wall.

5 Results

The transient pressure recorded at the middle pressure gauge in the incident sub-assemblies during the test are shown in Figure 7. The pressure recorded in the water outside the assembly, opposite stack 4 is shown in Figure 8. The transient outward displacement of the concrete blocks of stack 4 is shown in Figure 9. The initial and final positions of the blocks in the six stacks are given in Tables I and II.

The damaged incident sub-assembly is shown in Figure 4. The crushing of the sub-assemblies in section was measured at intervals of 305 mm starting at a height of 152 mm above the base plate, using the special profile measuring machine. The maximum crushing occurred at a height of 1530 mm and the re-assembled section through the core is shown in Figure 11. The amount of bending of the sub-assemblies is given in Table III.

The crushable fuel pins replacing the mild steel rods in the sub-assembly were recovered uncrushed although one of them was cracked.

The high speed cine film showed the gas bubble expanding from the top of the cluster but measurements soon became impossible because of turbulence and rapid clouding of the water.

6 Discussion

The transient pressure at the middle pressure gauge in the incident sub-assembly plotted in Figure 7 is compared in Figure 10 with the pressure measured at the same position in the earlier 19 sub-assembly experiment. The pressures can be seen to be very similar, indicating that the charge has burned and that both the 19 and 61 sub-assembly models have responded in very similar ways. The pressure measured in the overstrong sub-assembly with a fixed vent, when the same charge was burned in the gas producer, is also shown in Figure 10 and is very much larger and of longer duration, indicating that the rapid bursting of the incident sub-assembly in the simulated core experiments has provided very considerable venting of gas from the gas producer. The same mechanism of venting would occur in a vapour explosion in a sub-assembly in a real fast reactor.

The transient deflections of the concrete blocks of between 60 mm and 90 mm is greater than anticipated and has a wide spread. A plot of the transient displacement of Block β is given in Figure 9. From an examination of displacement A in Table I it would appear that block γ hinged about the outer edge in contact with block β and gave an unrealistic value for the transient deflection. It would be fairer to accept the displacement of Block β as more representative of the movement, particularly as the restraint springs acted over the whole of this block.

The deformation of the sub-assemblies extends out to the third row in all the sections and out to the fourth row over the length of the maximum split in the incident sub-assembly Figure 11. Some of the corner sub-assemblies show excessive deformation compared with the remaining sub-assemblies in the outer row. This may be due to the movement of the concrete blocks trapping these sub-assemblies between them. These sections do not illustrate sufficiently the bending of the sub-assemblies or guide tubes and this is shown more clearly by Table III.

The method of attaching the control rod guide tubes to the base plate allowed them to move up to 25 mm from their original positions. It is possible that this movement has affected the way in which the sub-assemblies deformed and the deformation of the guide tubes themselves, and in any future tests the guide tubes must be more securely fixed as in a typical fast reactor. The behaviour of the simulated control rod within the guide tube was masked by the fact that the wooden structure supporting the shroud tube frame was struck by the top concrete block of stack 2 Figure 6. This tore the wooden structure away from the shroud tube frame and allowed the frame to fall onto the cluster where it was supported by the sub-assemblies. It is probable that while falling the control rod struck the inside surface of its guide tube and sheared the retaining pins.

The damage to the incident sub-assembly was greater than for the 19 cluster assembly in that the split was longer and opened wider, giving a larger aperture for the release of the gas pressure. The rivets holding the mixer pin section to the main section were intact except where the split intruded into the rivetted area. This would indicate that even taking account of the shroud tubes and frame falling onto the incident sub-assembly and providing extra mass, the missile hazard is not serious.

7 Conclusions

This test has indicated that the damage from a "SPERT" vapour explosion as defined in Section 2.2 would probably not prevent the outer control rods from functioning.

The sub-assembly distortions were larger than expected, but the fuel pins would probably remain intact, and there is apparently no missile hazard from the mixer pin section. The reactivity change caused by the outward motion should be sufficient to shut the reactor down. The return motion and possible recompaction has to be considered from the reactivity point of view, but it should be noted that the present model does not provide an accurate simulation of typical recompaction conditions.

The main defect of the model was in the design of the bottom fixations of the control rod guide tubes and the absence of the sub-assembly spigots. This has probably allowed the displacements of the sub-assemblies to be too large in the experiment, and the results obtained probably do not represent a good simulation of the total core damage to be expected in a reactor. The experiment needs to be repeated with improved simulation of a core support structure. However, from the results obtained here it is clear that the dismantling of the core by the reactor operators after an incident of this kind could be extremely difficult because the crushing and bending of the sub-assemblies prevent them from being extracted by a straight vertical lift.

8 Acknowledgements

The authors would like to thank Mr A Brady for the detailed design of the model.

References

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[2] DENNY, P H., and WARREN, G R., Private communication.

[3] TEAGUE, H J., Private Communication.

[4] WARREN, G R., "The production of a gaseous explosion to simulate the thermal interaction between fuel and sodium coolant in sub-assemblies of a fast reactor". Paper E1/6 Second International Conference on Structural Mechanics in Reactor Technology, Berlin, September 1973.

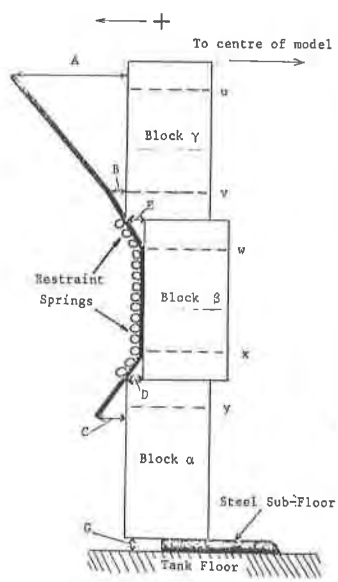


TABLE I

Distortion of Steel Bars and Displacement of Concrete Blocks

Stack		1	2	3	4	5	6	
Displacement	A	266	89	0	121	152	152	
	B	51	25	0	25	32	29	
	C	114	70	0	0	76	127	
	D	LHS 64 RHS 32	25	0	0	38	25	) Block β
								) taken as
	E	13	−13	0	0	9	13	) Datum
Bolts	u, v	Sheared	Sheared	Intact	Sheared	Sheared	Sheared	
	w, x	Intact	Intact	Intact	Intact	Intact	Intact	
	y	Sheared	Sheared	Sheared	Intact	Sheared	Sheared	
Gap	G	0	0	0	0	0	0	
Max. Defl.								
Block	α	(Gauge			24			
Block	γ	damaged)		76			152	

All dimensions in mm

TABLE II

Position of Concrete Stacks

Stack	Before Test			After Test		
	L/H Corner	Centre	R/H Corner	L/H Corner	Centre	R/H Corner
1						
R	1445	1337	1327	1448	-	1334
θ	91¼	115	140	91	-	139½
2						
R	1323	1137	1089	1346	1181	1150
θ	141½	167¼	197½	143¼	168½	197½
3						
R	1080	903	932	1099	927	953
θ	198	230¾	268½	200½	232½	269
4						
R	913	875	1072	946	902	1080
θ	271½	309¼	342½	271	307½	340½
5						
R	1084	1156	1356	1113	1164	1340
θ	344¾	14	40	344	14	39½
6						
R	1329	1329	1424	1327	-	1435
θ	40¾	66	90	41½	-	90½

Dimension R in mm — Distance along a radius from the centre of the tank floor.

Dimension θ in degrees — Angular displacement from a base line joining the centre of the tank to a fixed point on the tank wall.

TABLE III

Bending of Sub-Assemblies and Guide Tubes

Level in mm	152 (6")	457 (1'6")	762 (2'6")	1067 (3'6")	1372 (4'6")	1549 (5'1")	1676 (5'6")	1981 (6'6")	2286 (7'6")	2591 (8'6")
Sub-assembly										
0101	2.5	5.0	6.0	34.0	54.0	59.0	50.0	7.5		
0201	0	0	2.0	15.0	25.0	29.0	26.0	8.0		
0302	0	0	0	12.0	28.0	30.0	21.0	5.0		
0202	1.0	2.0	6.0	14.5	26.0	21.5	21.0	7.5		
0103	1.0	2.0	5.0	20.0	31.0	34.0	32.5	6.0		
0206	0.5	2.0	3.0	3.5	16.5	17.0	12.5	2.5		
0301	0	0	5.0	10.5	15.0	16.0	13.0	4.0		
0402	0	0	2.0	5.0	6.0	6.5	6.0	2.0		
0404	0	0	0	2.0	5.0	6.0	6.0	2.0		
0303	0	1.0	3	5.5	8.0	8.0	7.0	2.5		
0203	0	0	1.0	5.0	10.0	11.0	9.0	3.0		
0104	0	0	3.0	7.5	17.0	21.0	20.0	5.5		
0105	0	0	2.0	7.5	11.0	16.0	14.5	0		
0106	0	1.0	4.5	9.0	18.0	21.0	19.0	2.0		
0406	0	0	0	1.5	4.0	4.5	5.0	2.0		
0204	0	0	1.0	5.0	9.5	9.0	6.5	2.5		
0205	0	0	0	4.0	8.5	9.0	8.0	4.0		
0505	0	0	0	2.0	4.0	5.0	2.5	0		
0410	0	0	0	2.0	5.0	5.0	5.0	1.0		
0506	0	0	0	2.0	2.0	3.0	5.0	1.0		
Guide Tubes										
0403	0	4.0	6.0	7.0	9.0	10.0	9.0	9.0	5.0	1.0

Sub-assemblies:- Displacement from a line joining the base to the 2134 mm level.

Guide Tube:- Displacement from a line joining the base to the 2845 mm level.

Displacement in mm

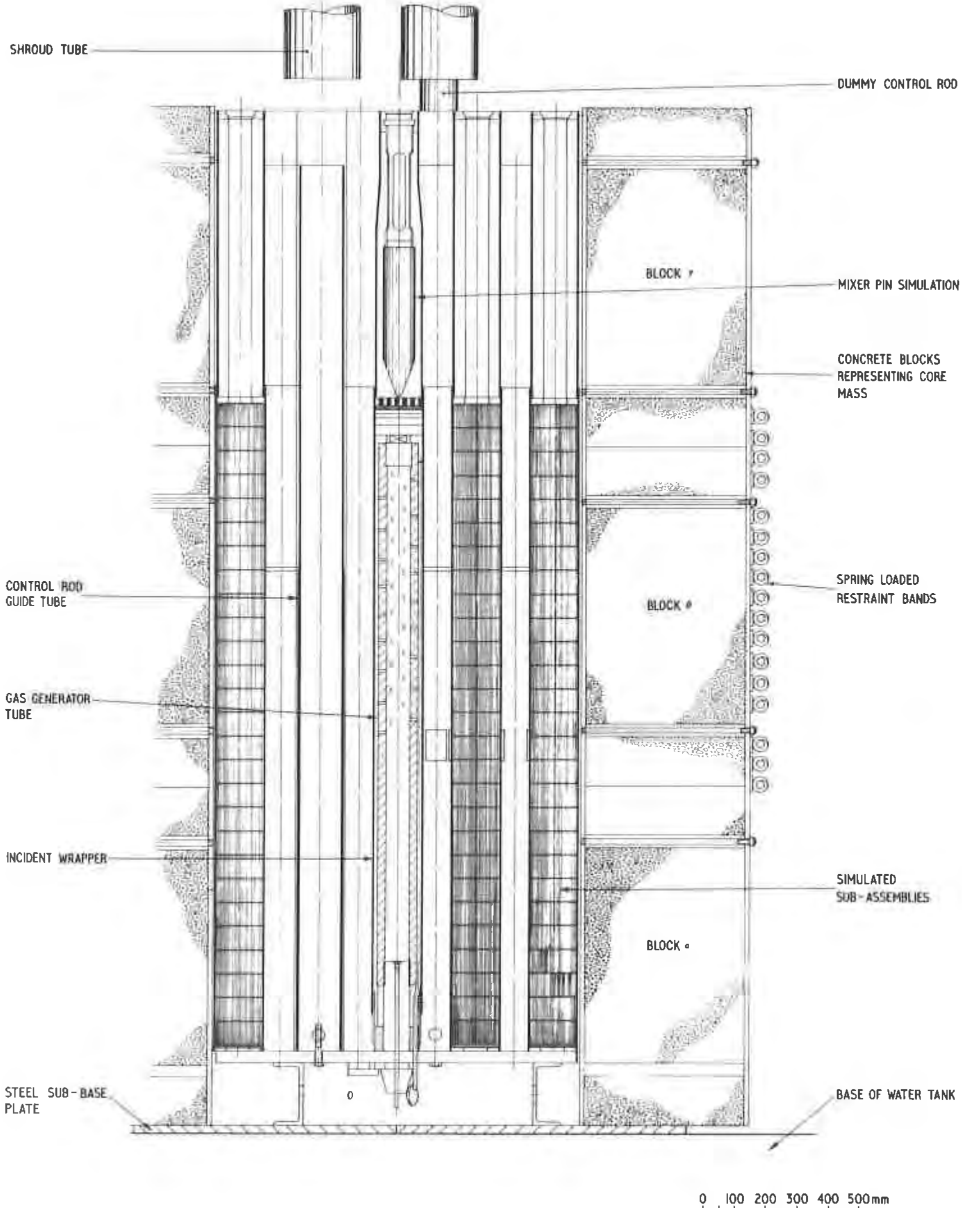


FIGURE 1. SECTION OF THE 61 SUB-ASSEMBLY MODEL

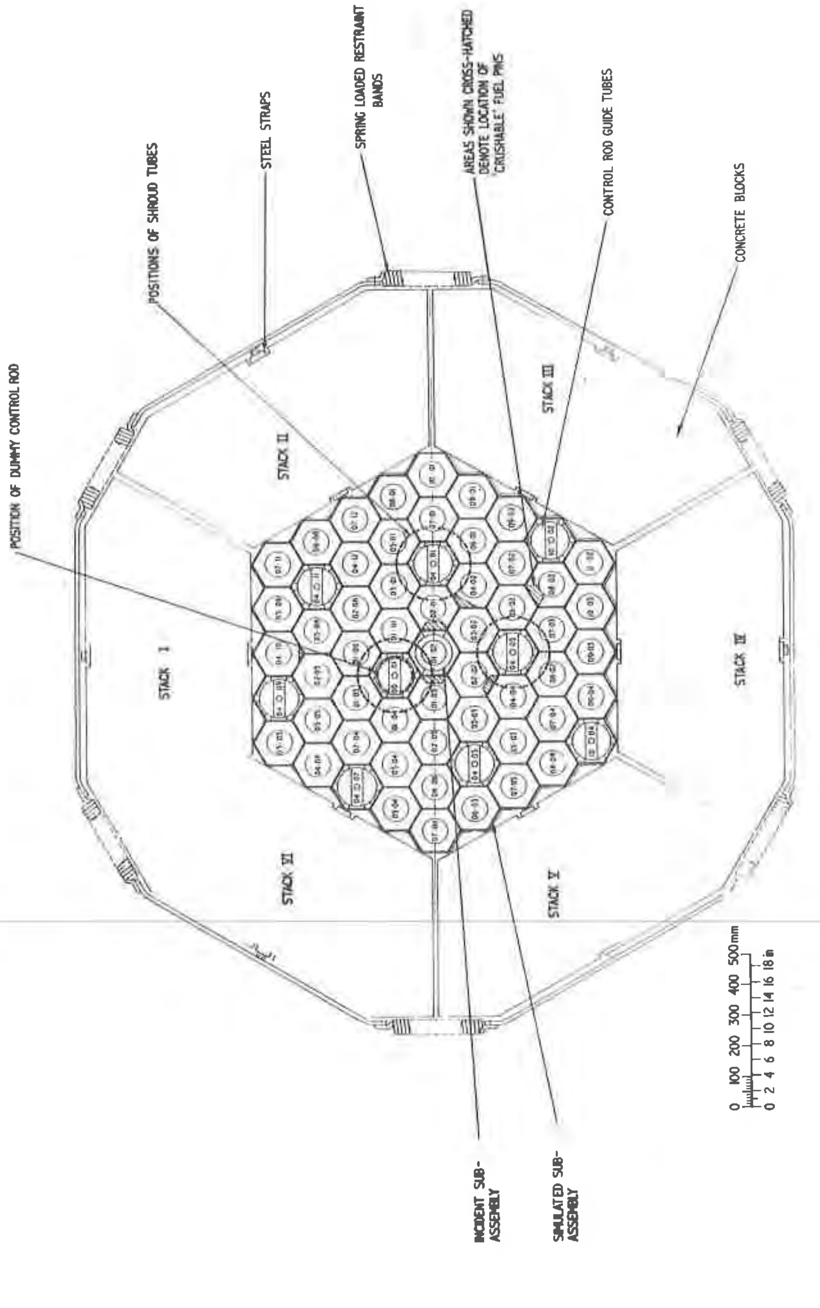


FIGURE 2 PLAN VIEW OF 61 SUB-ASSEMBLY MODEL

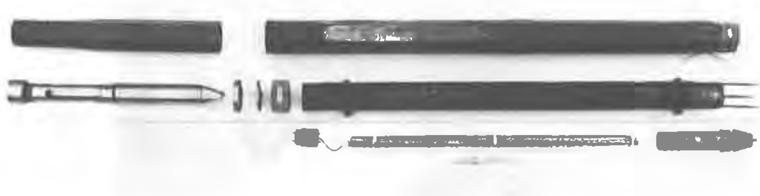


Figure 3   Exploded View of Central Sub-assembly and charge

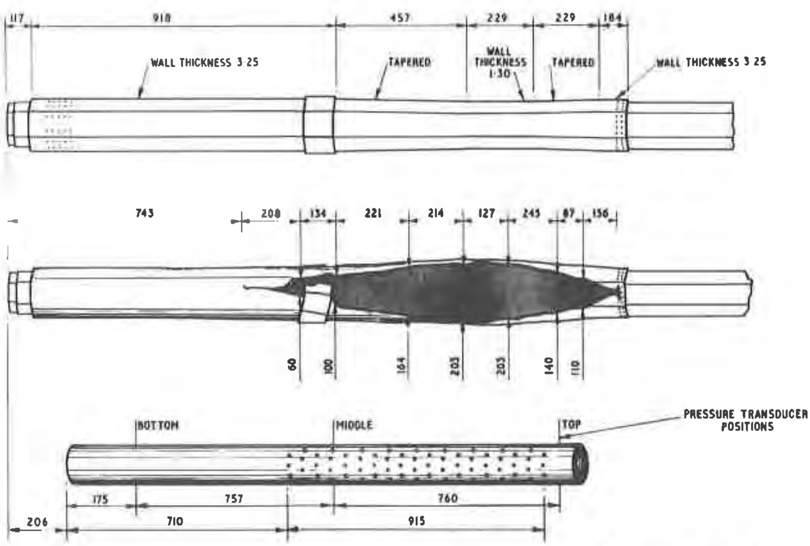


FIGURE 4. THINNED INCIDENT SUB-ASSEMBLY BEFORE AND AFTER TEST. SHOWING SPLIT RELATIVE TO GAS GENERATOR VENTS

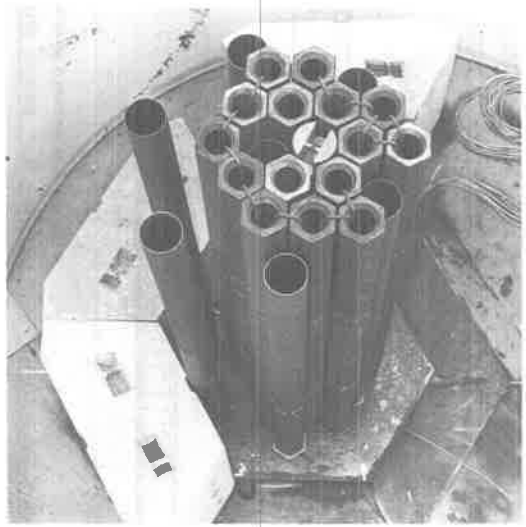


Figure 5   Guide Tubes and Second Row of Sub-assemblies during assembly of the Model

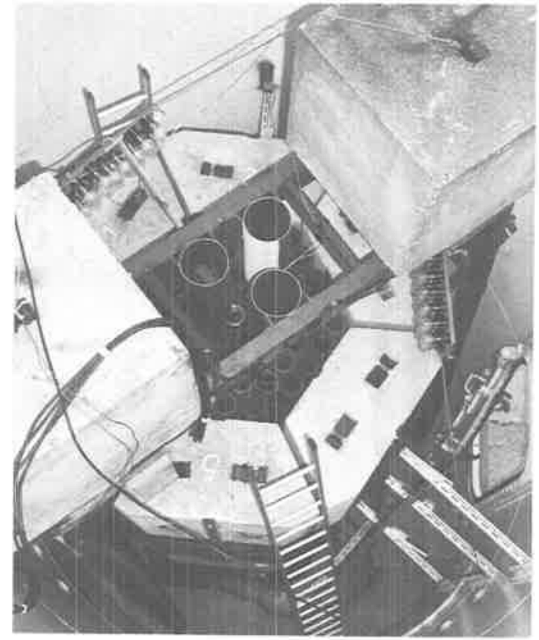


Figure 6   Top View of Fully Assembled Model

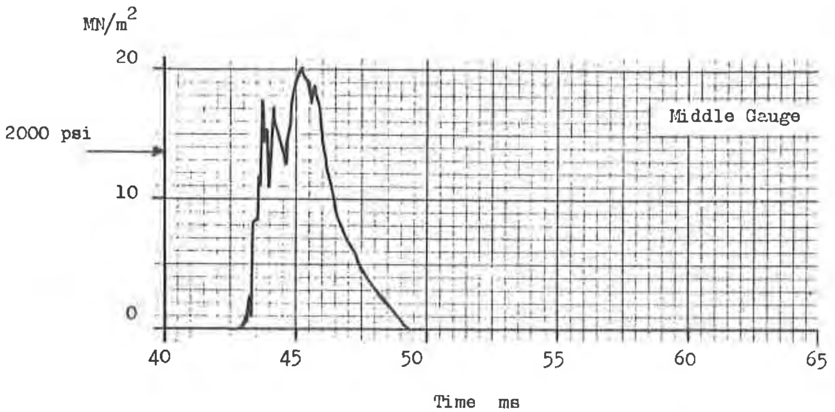


Figure 7 Transient Pressure at middle gauge in incident sub-assembly.

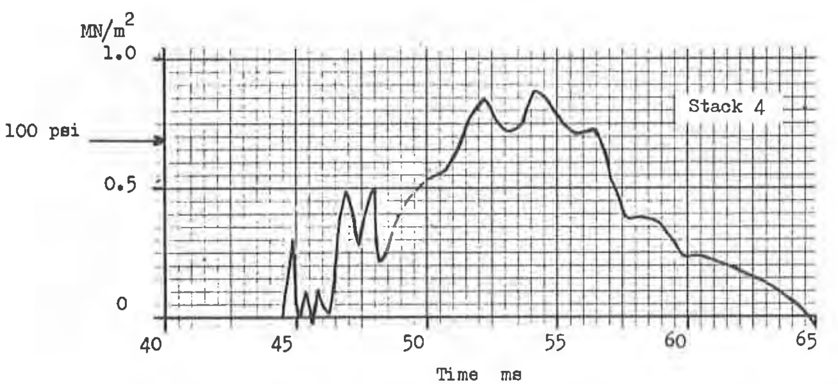
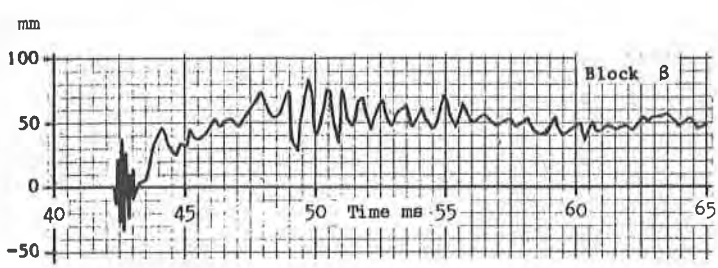


Figure 8 Transient Pressure in water outside assembly opposite Stack 4



Gauge undamaged and detached from block

Total travel 60 mm

Figure 9 Transient outward Deflexion of Stack 4 (Block β)

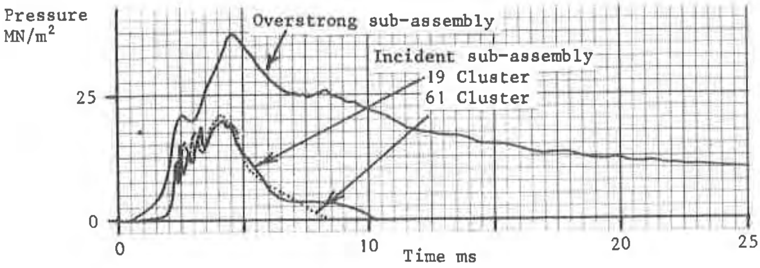


Figure 10 Comparison of Transient Pressures in an overstrong sub-assembly and the incident sub-assemblies in the Model tests

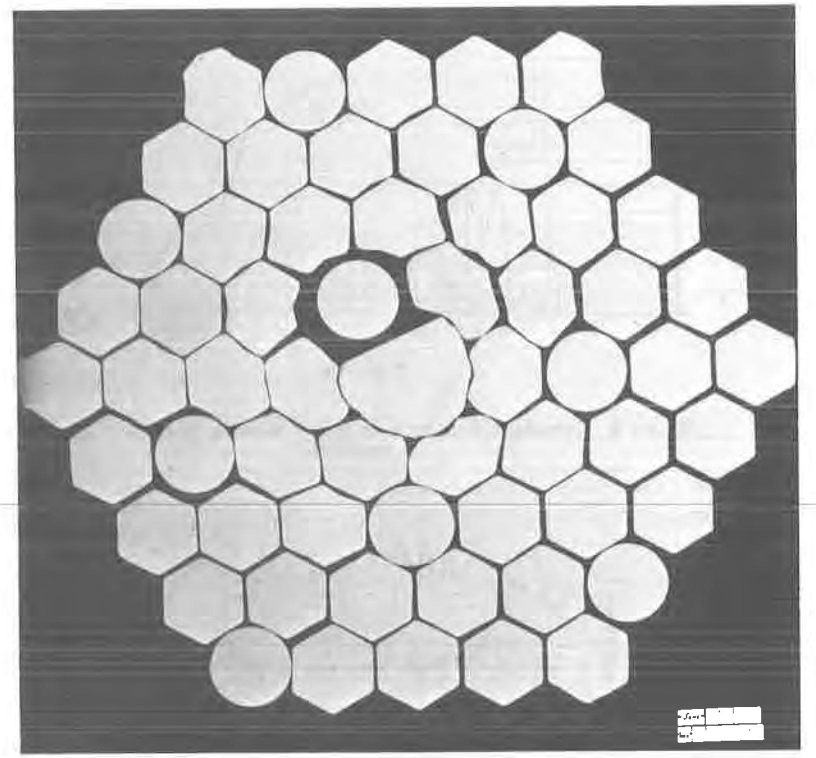


Figure 11 Section Through the Sub-assemblies at the level of Maximum Damage (5 ft 1 in. above base)