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Experimental Tests for Structural and Functional Verification of PEC Fast Reactor Core Elements with Seismic Loadings

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Abstract

The paper presents the results of the experiments carried out for structural and functional verification of PEC Fast Reactor core elements under seismic loadings. The experimental tests, carried out at AGIP/Medicina Laboratories within an agreement with the Fast Reactor Departure ENEA, were performed applying shock loadings on elements shrouds and cyclic and collapse loadings on element foot. Verification criteria were elaborated by ENEA related to French standards. The tests results allowed the element structural and functional requirements to be verified; furthermore, they provided reliable data for improving the validation of the French CASTEM computer code system, as well as adequate shock stiffness values to be used in the final calculations of the pec core seismic response.

1. Introduction

Experiments for the seismic verification of each type of PEC Fast Reactor core elements, were carried out for both 1/2 TSS and TSS conditions /1/ at AGIP/Medicina Laboratories, within an agreements with the ENEA Fast Reactor Department. The main objectives of these tests were:

- the seismic verification using criteria elaborated by ENEA, related to French standards, in order to avoid the excessive deformation, plastic instability, fatigue, progressive deformation or rupture under seismic loadings (Tab.I,II,III)
- the assessment of reliable data, allowing a contribution to be provided to the validation of the French CASTEM computer code system, which is used for the PEC core element design and thermo-mechanical verification
- the determination of adequate shock stiffness values to be used in the final core seismic calculations /1,2/.

2. Test specimens

The tests were performed on the element components which are subjected to the most severe seismic loads, i.e. (Fig.1):

- the shrouds at lower pad level (i.s. at 1440 mm from element base, below the active zone), considered to be subjected to "Neutron flux damage" (Tab.I);
- the shrouds at upper pad level (i.e. at 2558 mm from element base, above the active zone), considered to be not subjected to "Neutron flux damage" (Tab.II);
- the feet inserted in the corresponding cans, obviously assumed to be without "Neutron flux damage" (Tab.III).

Both the original shroud and foot geometries and those with the recent design modifications were analyzed /2/.

3. Test equipment

Tests on shrouds and feet were performed using two different equipments based on two hydraulic actuators of 7 and 50 tons respectively, both controlled by the same computer used also for data acquisition during all static tests. Shock tests on shrouds were performed at room temperature and data acquisition of the strain-gauges mounted on all specimens, dynamic load cell and displacement transducer were performed using magnetic and transient digital recorders(Fig. 2). Static tests on feet were performed at 400°C using a special furnace fitted on the foot and can assembly (Fig.3). Data acquisition of the high temperature strain-gauges mounted on feet and cans, load cell and displacement transducers were performed by means of the same computer program used also to program the test load history. Similar computer program has been also used for static collapse tests on shrouds.

4. Test load

The seismic loads applied to the pad levels were the maximum shocks forces computed with the computer code CORALIE for each element (Tab.IV) /2/, with further experimental information obtained in the ISMES shock tests of ref. /3/ (impact duration, time interval between subsequent shocks, loading rate). The shock forces were conservatively assumed to act simultaneously on two opposite faces of the shrouds. The seismic conditions were simulated (again conservatively) by 100 xn cycles, were n is the number of 1/2 TSS and 1 TSS earthquakes during the element life (1 TSS is assumed for all elements while the number of 1/2 TSS eartchquakes is less than five, depending on the "life" of the elements inside the reactor /1/). The seismic loads applied to the element feet were static, corresponding to the maximum displacement values (in both the positive and negative directions) computed with CORALIE at upper pad level (Tab.V) /2/; the seismic conditions were simulated with 10 xn cycles.

5. Test procedure

The shock test procedures were as follows:

- All tests were performed on virgin material at room temperature. The presence of neutronic damage is the main reason of the conservative assumption of 100 xn cycles, mentioned in Par. 4. Furthermore, the specimen were slightly too short, thus compensating temperature effects, as shown by 3D calculations based on experimental results.
- One or three adjacent faces of the hexagonal pads were constrained, opposite to the loaded face: this provides conservative test conditions.
- The dynamic loading consisted in the mentioned shock series, followed by dynamic or static collapse.

The feet tests procedures were as follows:

- All tests were performed at the nominal temperature of 400°C.
- All tests were performed taking in account the real foot-can couplings.
- The static loading consisted in the mentioned cycling followed by static collapse, or directly by static collapse.

6. Test results

The measurements involved static and dynamic loadings, shroud squeezings and strains, foot strains and transverse displacements. The excessive deformation loads and the collapse loads were determined from the collapse curves. These loads, reduced with appropriate safety factors, were used to give the structural limits for 1/2 TSS and TSS (Tabs.I-III); the residual strains and displacements were measured from cycling tests. These results are compared to the functional limits of the elements; from the above tests the total maximum strain ranges were evaluated, as well as the cumulated plastic strains and the number of cycles to reach shake-down conditions. After cycling tests, all tested components were submitted to liquid penetrant controls. All shroud and foot test results are reported in Tab.IV and V respectively. Figs.4 and 5 show the fuel element foot collapse and cycling curves, respectively. Fig.6 shows the shroud dynamic collapse curve at lower pad level and Fig.7 shows the time-histories of loading and displacement for a single shock of the same curve. Fig.8 shows the same collapse curve with the corresponding residual displacement curve and the procedure to determine the mentioned load for the structural seismic verifications. Fig.9 shows the shroud dynamic and static collapse curve with the corresponding residual displacement curve of the fuel element at the upper pad level.

7. Conclusions

The tests demonstrated that the structural and functional requirements of all PEC elements are satisfied (Tab.IV and V). With regard to the feet, this confirmed the adequacy of the analysis recently carried out to design the actual modified element feet /2/; in that analysis foot profiles had been designed such as to guarantee that upset limits are verified in the case of 1/2 TSS (with the assumption that the element motions at 1/2 TSS correspond to the maximum values which are geometrically possible taking into account the gaps among elements and that between the core and restraint ring). A similar conclusion can be drawn with regard to the most recent design analysis of the shrouds at pad level. Furthermore, useful data become available for the validation analysis of the French computer codes TEDEL, INCA, TRICO and BILBO of the CASTEM System (mainly in the elasto-plastic region), which is now in progress in the framework of the collaborative agreement between CEA and ENEA. Finally, reliable shock stiffness values were determined, which are now being used in the final CORALIE calculations of the PEC core seismic response.

REFERENCES

/1/ MARTELLI,A., "Methods for the Seismic Verification of a Fast Reactor Core", this Conference (EK2/1*).

/2/ CECCHINI,F., DI FRANCESCA,R., MARTELLI,A., MELLONI,R., MURATORI,P.G., MARESCA,G., "Feedbacks on PEC Fast Reactor Core Design due to Seismic Conditions", this Conference (EK2/6).

/3/ BONACINA,G., CASTOLDI,A., ZOLA,M., MARTELLI,A., SARTORI,C., VINCENZI,D., "Response to Impacts of Fast Reactor Core Elements during Seismic Excitation", this Conference (EK2/4).

TABLE I - STRUCTURAL CRITERIA FOR PEC CORE ELEMENT SHROUDS AT LOWER PADS

CRITERIA LEVEL	LOADING	T(°C)	ELASTIC ANALYSIS	ANELASTIC ANALYSIS	EXPERIMENTAL ANALYSIS	DAMAGE TO BE AVOIDED
A	monotonic $\frac{TSS}{2}$ shock	400	$P_m \leq \frac{R_m^{min}}{4.5}$	$\frac{P_{TSS}}{2} \leq \frac{P_{DE}}{1.5} = P'_{DE}$	$\frac{P_{TSS}}{2} \leq \frac{P_{DE}}{1.5 \times 1.5} = P'_{DE}$	Excessive deformation
			$P_L + P_b \leq \frac{R_m^{min}}{3}$	$\frac{P_{TSS}}{2} \leq \frac{P_C}{2.5} = P'_C$	$\frac{P_{TSS}}{2} \leq \frac{P_C}{1.5 \times 2.5} = P'_C$	Plastic instability
	cyclic $n \times 10 \frac{TSS}{2}$ shock series	400	$K^2 \varepsilon_t \leq \frac{A_R^{min}}{2}$ % $P_L + P_b + Q + F \leq \frac{2}{3} \sigma_Y^{min}$ $\frac{n \times 10 \times 10}{N} < 1$	$\frac{n \times 10 \times 10}{N} < 1$	no cracks with $n \times 10 \times 10$ shock series	Fatigue
			$P_L + P_b + Q \leq \frac{2}{3} \sigma_Y^{min}$	$(\tilde{\varepsilon}_m)_p < \frac{A_R^{min}}{2}$ % $(\tilde{\varepsilon}_m, \tilde{\varepsilon}_b)_p < \frac{2}{3} A_R^{min}$ %	$(\varepsilon_{loc})_p < 2\%$ shakedown	Progressive deformation
D	monotonic TSS shocks	400	$P_m \leq 2 \frac{R_m^{min}}{4.5}$	$P_{TSS} \leq \frac{P_C}{1.5}$	$P_{TSS} \leq \frac{P_C}{1.5 \times 1.5} = P''_C$	Plastic instability
	10 TSS shock series		$P_L + P_b \leq R_m^{min}$	$\varepsilon_p \leq A_R^{min}$ %	no rupture with 10 x 10 shock series	Rupture

- Material : AISI 316 20% CW
- Neutronic Damage : $\phi L > 5$ DPAF
- σ_Y, R_m, A_R% and fatigue curves : mechanical characteristics of irradiated material

TABLE II - STRUCTURAL CRITERIA FOR PEC CORE ELEMENT SHROUDS AT UPPER PADS

CRITERIA LEVEL	LOADING	T(°C)	ELASTIC ANALYSIS	ANELASTIC ANALYSIS	EXPERIMENTAL ANALYSIS	DAMAGE TO BE AVOIDED
A	monotonic $\frac{TSS}{2}$ shock	540	$P_m \leq S_m$	$\frac{P_{TSS}}{2} \leq \frac{P_{DE}}{1.5} = P'_{DE}$		Excessive deformation
			$P_L + P_b \leq 1.5\ S_m$	$\frac{P_{TSS}}{2} \leq \frac{P_C}{2.5} = P'_C$		Plastic instability
	cyclic $n \times 10 \frac{TSS}{2}$ shock series + 52 cyclic operations	540	$\frac{n \times 10 \times 10}{N} < 1$	$\frac{n \times 10 \times 10}{N} < 1$	no cracks with $n \times 10 \times 10$ $\frac{TSS}{2}$ shock series	Fatigue
			$(P_m)_E \leq 1.2\ S_m$ $(P_L + P_b)_E \leq 1.8\ S_m$ or $(P_L + P_b)_{max} + \Delta Q \leq 3\ S_m$	$(\tilde{\varepsilon}_m)_p < 1\%$ $(\tilde{\varepsilon}_m + \tilde{\varepsilon}_b)_p < 2\%$	$(\varepsilon_{loc})_p < 2\%$ shakedown	Progressive deformation
D	monotonic TSS shock	540	$P_m \leq \begin{cases} 2.4\ S_m \\ 0.7\ R_m^{min} \end{cases}$	$P_{TSS} \leq \frac{P_C}{1.5} = P''_C$		Plastic instability
	10 TSS shock series		$P_L + P_b \leq 1.5 \begin{cases} 2.4\ S_m \\ 0.7\ R_m^{min} \end{cases}$	$\varepsilon_p < A_R^{min}$ %	no rupture with 10 x 10 TSS shock series	Rupture

- Material : AISI 316 20% CW ($S_m = \frac{R_m^{min}}{2.7}$) AISI 316 annealed ($S_m = 0.9\sigma_Y^{min}$)
- Neutronic Damage : $\phi t < 5$ DPAF
- σ_Y, R_m, A_R% : mechanical characteristics of unirradiated material
- Fatigue curves : mechanical characteristics of irradiated material

TABLE III - STRUCTURAL CRITERIA FOR PEC CORE FEET ELEMENTS

CRITERIA LEVEL	LOADING	T(°C)	ELASTIC ANALYSIS	ANELASTIC ANALYSIS	EXPERIMENTAL ANALYSIS	DAMAGE TO BE AVOIDED
A	monotonic $\frac{TSS}{2}$	400	$P_m \leqslant S_m$	$\frac{P_{TSS}}{2} \leqslant \frac{P_{DE}}{1.5} = P'_{DE}$		Excessive deformation
			$P_L + P_b \leqslant 1.5\ S_m$	$\frac{P_{TSS}}{2} \leqslant \frac{P_C}{2.5} = P'_C$		Plastic instability
	cyclic $n \times 10\ \frac{TSS}{2}$ cycles	400	$V < 1$	$\frac{n \times 10}{N} < 1$	no cracks with $n \times 10$ cycles	Fatigue
			$P_L + P_b + \Delta Q \leqslant 3\ S_m$	$(\bar{\varepsilon}_m)_p < 1\%$ $(\bar{\varepsilon}_m + \bar{\varepsilon}_b) < 2\%$	$(\varepsilon_{loc})_p \leqslant 2\%$ Shakedown	Progressive deformation
B	monotonic TSS	400	$P_m \leqslant \begin{cases} 2.4\ S_m \\ 0.7\ R_m^{min} \end{cases}$	$P_{TSS} \leqslant \frac{P_C}{1.5} = P''_C$		Plastic instability
	cyclic 10 TSS cycles		$P_L + P_b \leqslant 1.5 \begin{cases} 2.4\ S_m \\ 0.7\ R_m^{min} \end{cases}$	$\varepsilon_p < A_R^{min}\ \%$	no rupture with 10 cycles	Rupture

- Material :
AISI 316 annealed
- $S_m = 0.9\ \sigma_Y^{min}$
- Neutronic Damage :
$\emptyset t < 5$ DPAF
- $\sigma_Y, R_m, A_R\%$ and fatigue curves :
mechanical characteristics of unirradiated material

TABLE IV - PEC CORE ELEMENT SHROUDS TEST RESULTS AND SEISMIC STRUCTURAL-FUNCTIONAL VERIFICATION

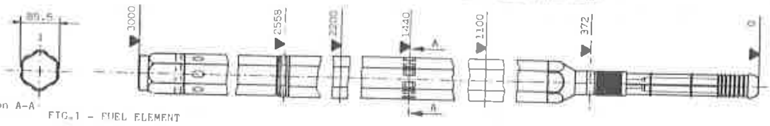
COMPONENT	TEST	SEISMIC LOAD DATA		RESULTS				ALLOWABLE SHROUD DEFORMATION		
Normally 1 contact		Event	Shock load assumed for verifications (Kg)	Structural limits (Kg)	Shock stiffness (Kg/mm)	Cycling cracks	Functional limits (2) corresponding to allowable displacement (Kg)	Event	Residual displacement (mm)	Load displacement (mm)
Fuel element lower pad shroud L = 130 mm	Single shocks and static collapse	TSS/2	440	$P'_{DE} = 840$ $P'_C = 613$	531		1530	Cooling	0.3	
		TSS	660	$P''_C = 1022$						
Fuel element lower pad shroud L = 130 mm	Single shocks and dynamic collapse	TSS/2	440	$P'_{DE} = 964$ $P'_C = 619$	438		1410	Cooling	0.3	
		TSS	660	$P''_C = 1031$						
Fuel element lower pad shroud L = 130 mm 3 contacts	Single shocks and static collapse	TSS/2	440	$P'_{DE} = 2018$ $P'_C = 1381$	4042		4320	Cooling	0.3	
		TSS	660	$P''_C = 2302$						
Fuel element lower pad shroud L = 493 mm	Cyclic shocks and dynamic collapse	TSS/2	440	$P'_{DE} = 1531$ $P'_C = 1305$	560	NO	3000	Cooling	0.3	
		TSS	660	$P''_C = 2175$		NO				
Forced type reflecting el. upper pad shroud L = 500 mm	Cyclic shocks and static collapse	TSS/2	1110	$P'_{DE} = 1167$ $P'_C = 2708$	1170	NO	2325	Shroud and NA no interference		1.1
		TSS	1780	$P''_C = 4513$		NO				
Fuel element upper pad shroud L = 500 mm orig. design	Cyclic shocks and static collapse	TSS/2	1110	$P'_{DE} = 911$ $P'_C = 2040$	985	NO	1937	Central track remaining in seat		1.7 (Hexcan diagonal)
		TSS	1780	$P''_C = 3400$		NO				
Fuel elem. upper pad shroud L = 500 mm final design	Cyclic shocks and static collapse	TSS/2	1100	$P'_{DE} = 2667$ $P'_C = 3120$	4170	NO	6000	Central track remaining in seat		1.7 (Hexcan diagonal)
		TSS	2200	$P''_C = 5200$		NO				
Control rod guide elem. upper pad shroud L = 500 mm	Cyclic shocks and static collapse	TSS/2	550	$P'_{DE} =$ [illegible] $P'_C = 2571(1)$	1377	NO	> 7000 (1)	Scram feasibility		12.4
		TSS	924	$P''_C = 4585(1)$		NO				
Neutron shielding el. upper pad shroud L = 500 mm	Cyclic shocks and static collapse	TSS/2	1177	$P'_{DE} = 3900$ $P'_C = 2800(1)$	1613	NO				
		TSS	1782	$P''_C = 4667(1)$		NO				

NOTE : (1) max load test facility = 7000 Kg
(2) the functional verification requires the functional limit load to be higher than TSS/2 load.

TABLE V - PEC CORE ELEMENT FEET TEST RESULTS AND SEISMIC STRUCTURAL-FUNCTIONAL VERIFICATION

COMPONENT	TEST	SEISMIC DISPLACEMENT DATA		RESULTS					FUNCTIONAL LIMITS	
		Event	Seismic displacement at 2558 mm (mm)	Seismic positive displacement load assumed for verification (Kg)	Structural limits (Kg)	Cycling cracks	Functional limit load(1) corresponding to allowable load displacement (Kg)	Residual TSS/2 (or TSS) displacement at 2558 mm assumed for verification (mm)	Event	Allowable residual (or load) displacement at 2558 mm (mm)
Forced fuel el. without higher sphere diameter reduction (0.06 mm)	Collapse	TSS/2	26	43	$P'_{DE} = 81$ $P'_C = 75$					
		TSS	29	47	$P''_C = 125$					
		max. geom. displacement at 2558 mm	36	60	$P''_C = 125$					
Forced fuel element	Cycling and Collapse	TSS/2	+ 29 - 25	39	$P'_{DE} = 51$ $P'_C = 56$	NO		0.9	20% forcing reduction	1.7
		TSS	+ 34 - 32	49	$P''_C = 93$	NO			handling	2.6
		max. geom. displacement at 2558 mm	+ 37 - 36	56	$P''_C = 93$	NO				
Forced fuel element	Collapse	TSS/2	29	39	$P'_{DE} = 69$ $P'_C = 72$					
		TSS	32	44	$P''_C = 120$					
		max. geom. displacement at 2558 mm	35	51	$P''_C = 120$					
Forced fuel el. with the strictest coupling condition	Cycling and Collapse	TSS/2	+ 26 - 23	37	$P'_{DE} = 66$ $P'_C = 68$	NO		0.2	20 % forcing reduction	1.7
		TSS	+ 31 - 26	47	$P''_C = 113$	NO			handling	2.6
Normal reflecting element	Cycling and Collapse	TSS/2	+ 25 - 25	45	$P'_{DE} = 60$ $P'_C = 71$	NO		0	handling	12.4 (360 GEPP)
		TSS	+ 30 - 31	55	$P''_C = 119$	NO				
		max. geom. displacement at 2558 mm	+ 42 - 42	73	$P''_C = 119$	NO				
Neutron shielding element	Cycling and Collapse	TSS	+ 24 - 16	41	$P'_{DE} = 64$ $P'_C = 134$	NO		0 (TSS)	handling	14
		max. geom. displacement at 2558 mm	+ 41 - 16	71	$P''_C = 178$	NO				
Control rod guide element	Cycling and Collapse	TSS/2	+ 24 - 19	51	$P'_{DE} = 62$ $P'_C = 74$	NO	68		no absorber elem. hold down system contact	32.9 (load displ.)
		TSS	+ 31 - 27	66	$P''_C = 123$	NO		1.2	handling	7

NOTE (1) the functional verification requires the functional limit load to be higher than TSS/2 load.



Section A-A

FIG.1 - FUEL ELEMENT

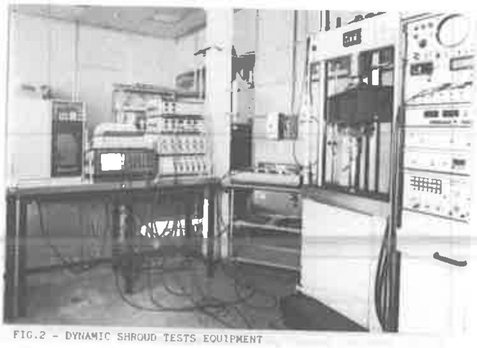


FIG.2 - DYNAMIC SHROUD TESTS EQUIPMENT

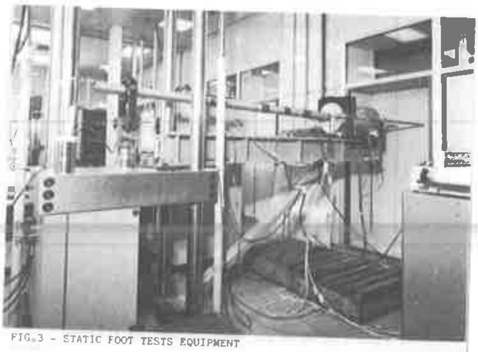


FIG.3 - STATIC FOOT TESTS EQUIPMENT

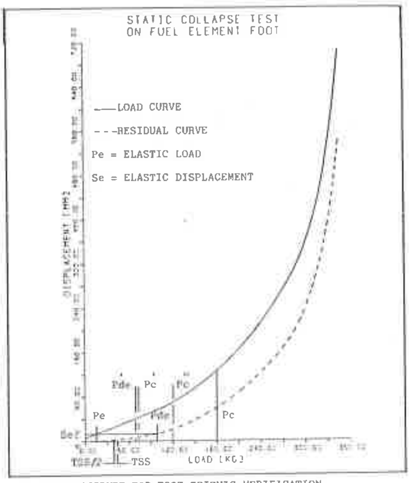


FIG.4 - PROCEDURE FOR FOOT SEISMIC VERIFICATION

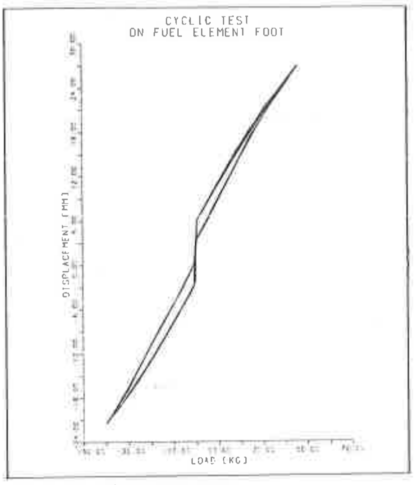


FIG.5 - TSS 1/2 FOOT CYCLIC TESTS

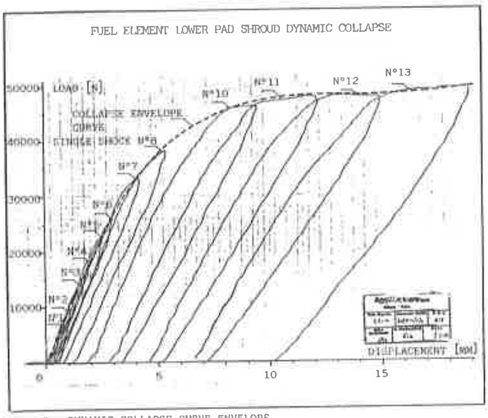


FIG.6 - DYNAMIC COLLAPSE CURVE ENVELOPE

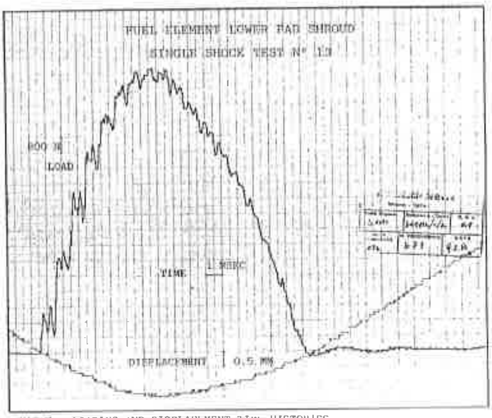


FIG.7 - LOADING AND DISPLACEMENT TIME-HISTORIES

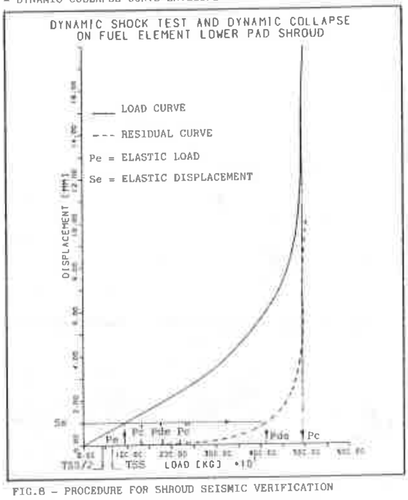


FIG.8 - PROCEDURE FOR SHROUD SEISMIC VERIFICATION

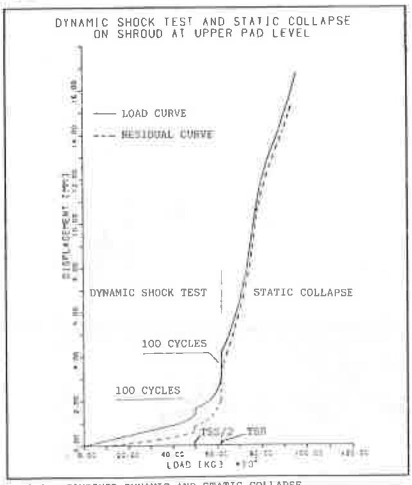


FIG.9 - COMBINED DYNAMIC AND STATIC COLLAPSE