Thermo-structural analysis and design verification of the PEC reactor vessel

F.Corsi, G.M.Giannuzzi & L.Sipione
ENEA, C.R.E., Casaccia, Italy
B.Taddia
ENEA, D.R.V., Bologna, Italy

ABSTRACT

The paper presents the main results of the detailed finite element analysis and the relevant verifications against the ratcheting event for the higher part of the PEC reactor vessel stressed by the presence of the axial thermal gradient caused by a sodium level.

A very refined finite element analysis with the Castem System, developed in CEA Saclay, was performed covering both the steady state and the transient thermal conditions.

Great care was taken for the simulation of the sodium level fluctuation within the gaps between the various thermal baffles just necessary to reduce the high thermal stresses.

A thermo-elastic structural analysis taking into account thermo-physical properties variable with temperature was then performed using the Inca computer code.

The mechanical loads considered in the analysis are the vessel weight and the loads caused by seisma.

Large attention was given to the design verification against the ratcheting event as proposed in the ASME N47 Tests, in particular as proposed in Test 3.

Different procedures were followed both using different stress classifications and different rules for the creep ratchetting strain evaluation.

The interesting relevant results are presented.

At last a detailed inelastic analysis and the relevant structural design verification are performed with a conclusive comparison with the elastic results.

1. INTRODUCTION

The study is performed to verify that the PEC reactor vessel is not effected by ratchetting during the presumed service life owing to the presence of the sodium level and its fluctuations.

A previous analysis showed in fact that this failure mode is the most critical for the component integrity.

2. PEC vessel operative functioning, boundary conditions, design data.

Fig. 1 shows the vessel geometry. In Fig. 2 it's represented the upper part of the vessel with the sodium level. In detail are shown the thermal baffles which have been designed to reduce to allowable values the axial thermal gradients caused by the sodium level.

The operative life of the PEC reactor has been scheduled to be 125.000 hours. The thermal loads have been defined taking into account the most critical cycles. This means to begin with the Cold Start-up which takes the reactor up to max temp. service life and to end with the transient ROPO, the most severe upset condition, which is characterized by a hot thermal drift and a cold thermal shock due to scram (Fig. 3).

Fig. 4 shows f.i. the boundary condition scheme assumed in the modellization relevant the ROPO transient thermal analysis.

3. Thermal Calculation Results.

Figg. 5 and 6 represents the temperature field history of the primary tank during the cold start up and the ROPO transient at different times. It's quite evident the presence of an hard thermal axial gradient while the gradient through the thickness appears to be not significant.

4. Thermomechanical Calculation Results and Design Verification.

Figg. 7 and 8 show VMISES, radial, axial and hoop components trends along the primary tank thickness for the most stressed section, respectively for the two thermal loads.

Design verification against ratchetting event is performed applying different stress classifications and different rules for the creep ratchetting strain accumulation.

In particular the standards and rules proposed in test 3 of ASME N47 and RCC-MR "Efficacity diagram" are used.

Tables 1, 2, 3 give the relevant results obtained with the different procedures.

A) 1 - Primary stresses P + S + M_t (Vessel weight, Seisme, Thermal Membrane Moment)
2 - Secondary stress F_t (Thermal Bending Moment)

B) The same than A but deducting to the calculated the seisme stress contribution.

C) Summing the two strain contribution and ,obtained by the only thermal load (M_t Primary, F_t Secondary) and mechanical primary (P-S) thermal secondary ($M_t + F_t$).

D) Efficacity Curve Rule

5. Remarks

A) The stress field is such that the structural behaviour of the component is near the in/on ratchetting threshold in the Bree diagram.

B) A little shifting on the stress values brings strong differences on the damage mode result verification.
An increment of 10% on stress components gives an ε_c value out of the creep curve, while a decrease of 10% makes the component structurally reliable and verified the criteria.

C) The results obtained in the different procedures seem to show not effectively critic the component to the ratchetting failure mode but necessary of further non linear analysis.

6. Inelastic Analysis and Design Verification.

Fig. 9 shows the load hystory defined for the creep-inelastic calculations.
The logic load sequence is assumed with the conservative criteria that the seisma happens just for each cycle at the time of maximum thermal stress.

Cycling elasto-plastic material features and the creep law are derived from ASME C.C. N 47 for AISI 316 Stainless Steel.

7. Results and Conclusive Remarks.

Figg. 10 ÷ 13 show clearly that the structural behaviour of the PEC vessel zone near the sodium level is very far from the ratcheting failure mode.

The results proves for this particular case the excessive conservativism of the rules proposed by ASME TEST 3 following an elastic structural analysis.

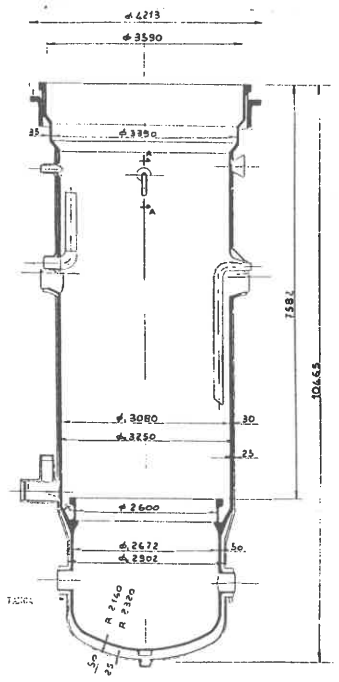

Fig. 1 - PEC Reactor Vessel

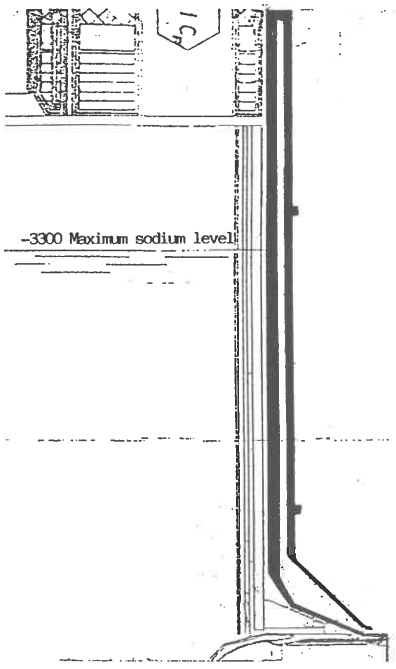

Fig. 2 - Thermal Baffles and Sodium Level Detail

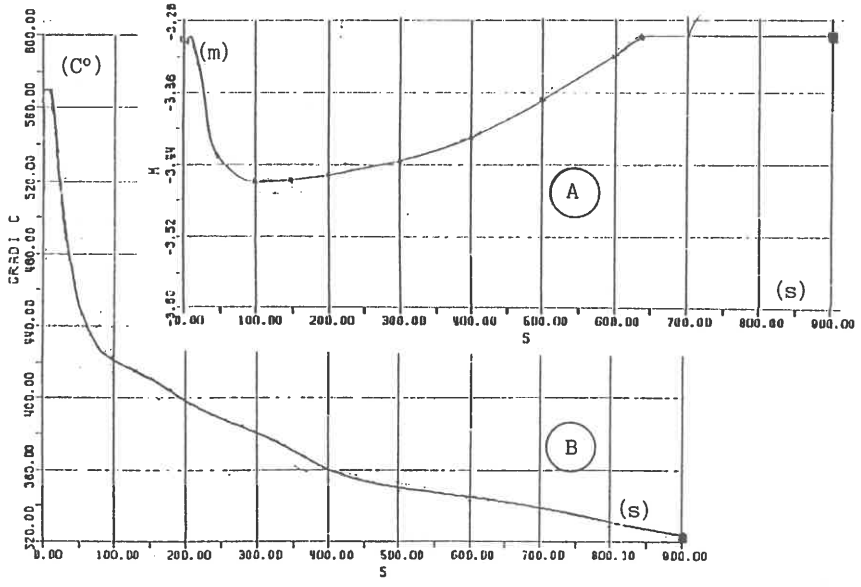

Fig. 3 - Sodium Level (A) and Temperature (B) Variation During RØPØ Transient

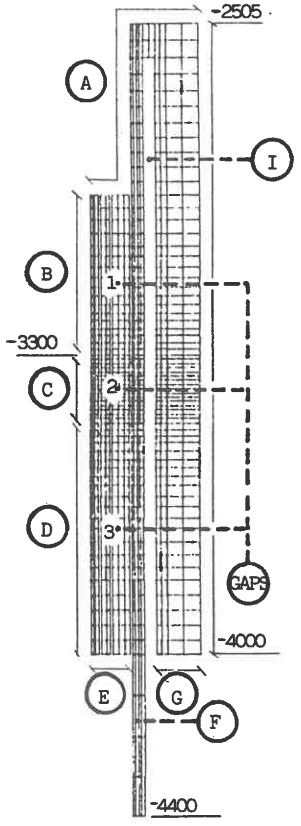

Fig. 4 - Structure Schematization and Different Boundary conditions.

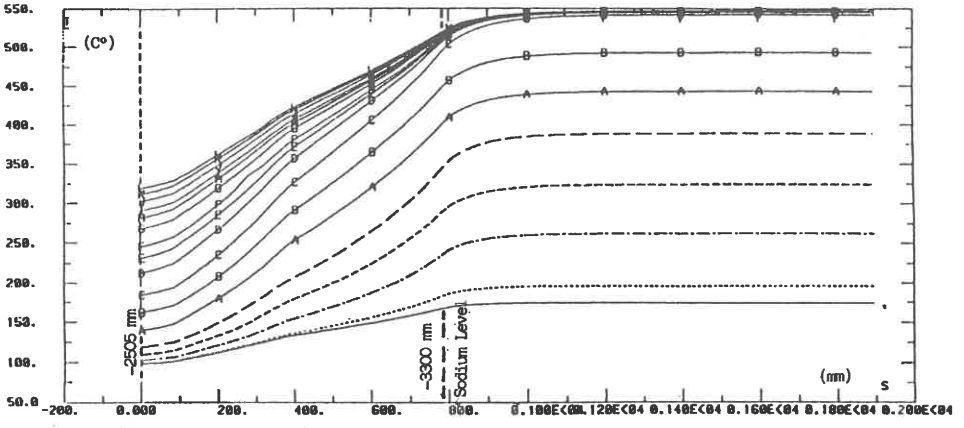

Fig. 5 - Thermal Field on the primary Vessel during the Cold-Start

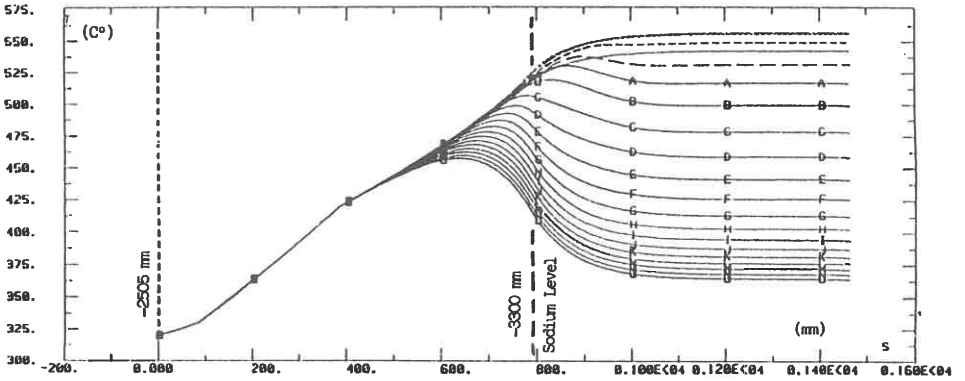

Fig. 6 - Thermal Field on the primary Vessel during the RØPØ transient

SECTION z-coordinate in mm.	H W/m²°C	Range Extremes sec.	T_{range} °C	P_{max} Kg/mm²	Q_R Kg/mm²	X	Y	S_y Kg/mm²	Z	σ_C Kg/mm²	$1.25\sigma_C$ KSI	T_{max} °F	ε_C %
23 - 3400	7000	P.F. 153600	528	7.4	20.2	0.58	1.6	12.67	0.97	12.3	21.8	991	1.3
		ROPQ 7000	378										
23 - 3400	1980	P.F. 153600	525	7.	19.2	0.55	1.52	12.62	0.87	11.	19.6	990	0.7
		ROPQ 7000	385										

Table 1 - Application of c.c. N47-18 ratchetting rules in classific A

SECTION z-coordinate in mm.	H W/m²°C	$\sigma_C - S$ Kg/mm²	ε'_C %
23 - 3400	7000	9.9	0.4
23 - 3400	1980	8.6	0.22

Table 2 - Application of c.c. N47-18 ratchetting rules in classific C

H W/m²°C	PRIMARY LOADS / SECONDARY LOADS	RANGE EXTREMES SEC.	T_{RANGE} °C	P_{MAX} Kg/mm²	Q_R Kg/mm²	X	Y	S_y Kg/mm²	Z	σ_C Kg/mm²	$1.25\sigma_C$ Kg/mm²	T_{max} °C	ε_C %	$\varepsilon_{C_{tot}}$ %
1000	M_T / F_T	P.F. 153600	528	6.1	20.2	0.48	1.6	12.61	0.78	9.8	17.5	991	0.4	0.43
		ROPQ 7000	378											
1000	P+S / M_T+F_T	P.F. 153600	528	3	21.7	0.24	1.72	12.67	0.43	5.4	9.7	991	0.03	
		ROPQ 7000	318											
1980	M_T / F_T	P.F. 153600	525	5.7	19.2	0.45	1.52	12.62	0.69	8.8	15.6	990	0.25	0.27
		ROPQ 7000	385											
1980	P+S / M_T+F_T	P.F. 153600	525	3	20.6	0.24	1.63	12.62	0.4	5.1	9	990	0.02	
		ROPQ 7000	585											

Table 3 - Application of c.c. N47-18 ratchetting rules in classific C

$$SR1 = \frac{\Delta Q}{P} = 2.7 \; ; \; V1 = 0.59 \; ; \; P_{eff} = 12.5 \text{ Kg/mm}^2$$

$$P_{eff} = 12.5 \text{ Kg/mm}^2 < P_{amm} = S_t = 12.6 \text{ Kg/mm}^2$$

Table 4 - Application of RCC-MR "Efficacity Diagram"

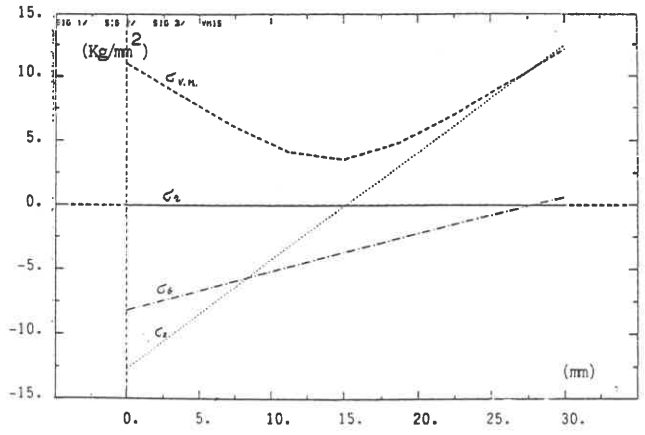

Fig. 7 - VMises and stress components trend along the primary Vessel most stressed Section in Cold Start-up

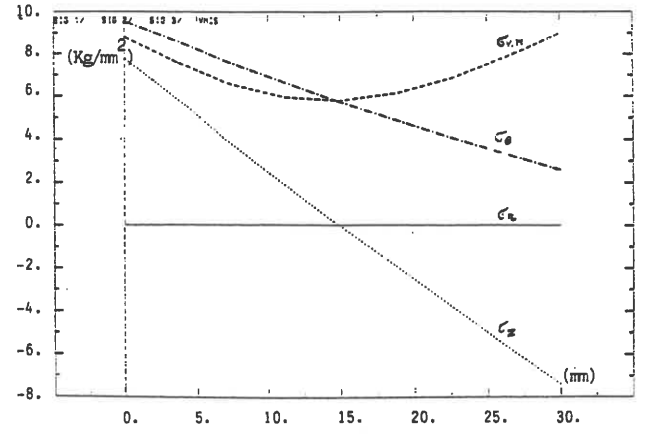

Fig. 8 - VMises and stress components trend along the primary Vessel most stressed Section in RØPØ transient

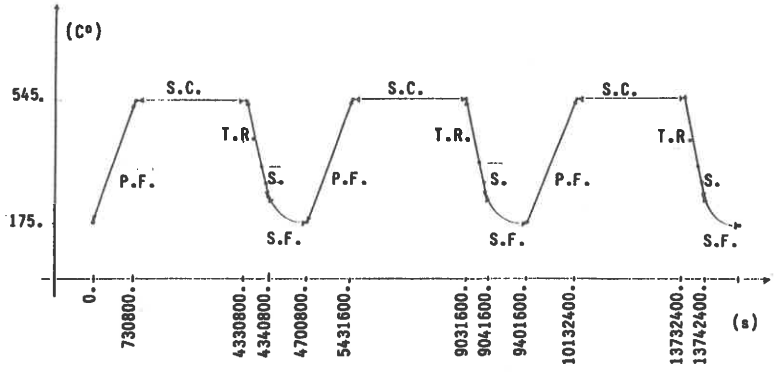

Fig. 9 - Load history in Inelastic Analyses

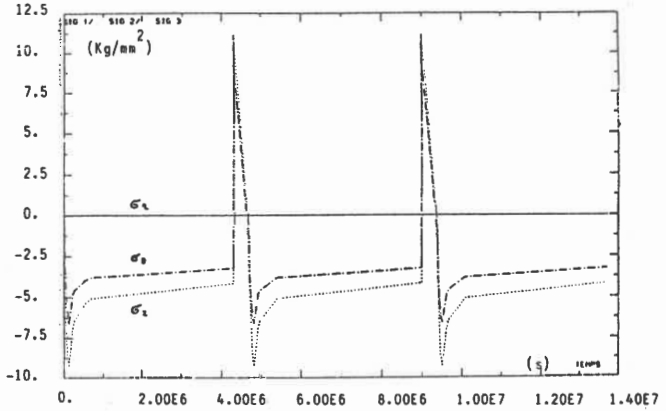

Fig. 10 - Stress Components Trend during the 3 cycles time

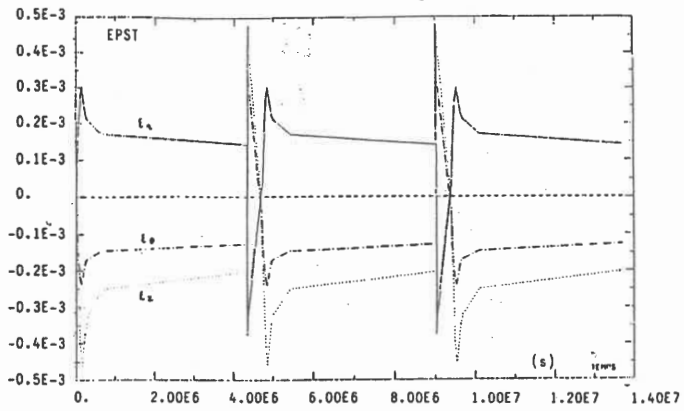

Fig. 11 - Strain Components trend during the 3 cycles time

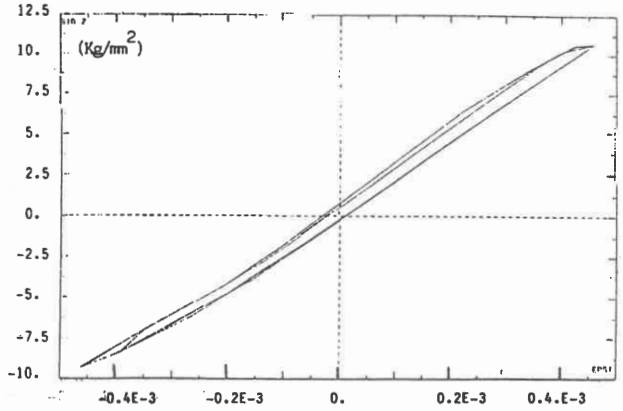

Fig. 12 - σ_z ε_z cyclic stress-strain curves for the for the internal point of the most stressed section

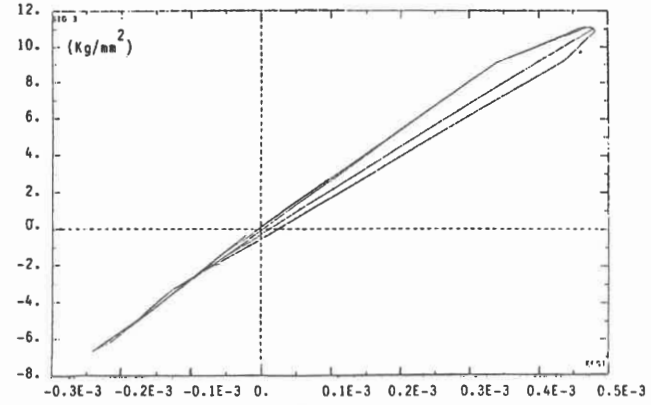

Fig. 13 - σ_θ - ε_θ cyclic stress-strain curves for the internal point of the most stressed section