Ultimate Strength and Rupture Modes for Metal Containment System Type Mark III Under Pressure Load Further Investigations

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INTRODUCTION

In the last few years, in particular, the analysis of the containment of NPP's has been developed including also "severe accident" conditions, supposing the unavailability of the emergency cooling systems, the core melting and subsequent possible break-through the RPV, the ablation of basemat and the heating and pressurization of the containment atmosphere.
In this paper the limit pressure to produce wide plastic flow and the impact of a crack on the integrity of the BWR containment vessel, type MARK III, have been assessed.
This evaluation is aimed at controlling the temperature and the pressure of the containment atmosphere by means of opportune systems, as relief valves and external spray cooling of the metal containment. Accordingly it has also been evaluated the capability of the containment to bear a flooding of the shield building annulus, above the penetration level, after an external spraying to remove the internal heating. The loss of integrity of the containment vessel can derive from an overall collapse as well as a localized failure. As to the first mode, an analysis has already been performed (G. Maresca, P.P. Milella, G. Pino, '88) using the FE INCA code of the CASTEM system .
The purpose of this paper is to further analyze the collapse mode and, in particular, to investigate the possibility of a localized failure. To this purpose the MARC code has been used to assess the integrity of a personnel airlock which represents one of the most significative discontinuity in the structure.
In this analysis two different models have been studied using the MENTAT-MARC system and the large displacement method : an axisymmetric FE model of the containment structure (FIG. 1) and a 3-D FE model of the personnel hatch penetration (FIG. 2).
The rupture modes considered are :
- plastic collapse,
- large deformation of the shell leading to the fall of the polar crane,
- collapse by vertical loads,
- crack instability in welding regions,
- small buckling from external hydrostatic loads (case of the external spray cooling).

MODELLING OF THE CONTAINMENT VESSEL

The containment vessel considered is the MARK III-Alto Lazio NPP with a total height of 58 m, mean radius of 18.3 m and 3.8 cm thick. The containment vessel material is : SA 537 Cl 1 (t < 2.5 inch) Ferritic Steel for Class MC Components. The bilinear stress-strain curve of SA 537 is shown in FIG. 3.

The limit temperature of the severe accident considered is 149°C (300°F), the yield strength, σy, is 285 MPa, the ultimate strength, σu, is 483 MPa and the flow stress is

$$\sigma f = \frac{\sigma y + \sigma u}{2} = 384 \text{ MPa}$$

The Young's modulus, E, is 2.E+05 MPa.
The containment vessel has been modelized with 332 nodes and 165 shell elements, with each element subdivided into 11 layers. In the model the four reinforcing ring girders and the ring supporting polar crane have been considered because they play an important role increasing the overall stiffness and decreasing the stresses and the circumferential strains.
In the personnel hatch penetration model 620 nodes and 564 elements have been used.

ANALYSIS OF THE SEVERE ACCIDENT TRANSIENT

The "severe acident" transient considered in the present analysis is shown in FIGs. 4 and 5.
The transient terminates at 4500 minutes, where the temperature and pressure saturate.
It was , instead, assumed a continuous growth of both the pressure and the temperature over 4500 minutes to investigate the ultimate conditions which would cause the global collapse of the structure. Figures 6 and 7 shows the transient actually considered in this analysis. The yield strength, flow and ultimate stress were varying accordingly. The hypotheses assumed for the severe accident are:
- station blackout,
- no core catcher,
- reactor cavity flooded with 10 m of water,
- upper pool refilling rate of 50 m /hr,
- design leakage of 1% vol/day,
- hydrogen ignition at 8% mole fraction.

The code used to assess the pressure peak was based on the MARCH 3 model (Meltdown - Accident - Response - CHaracteristics, NUREG/CR 3988). Shown in Fig. 4 is the peak pressure reached in the first 100 minutes. However with the MARCH 3 model the pressure builds up following the flame propagation velocity and it is not considered any possible dynamic pressure wave propagation effect resulting from a hydrogen explosion which may produce a further increase, of the peak pressure on the containment wall. This possible overpressure, which is extimated to be to 20 times higher, (J.H. Gittus, '82), has not been accounted for.
Furthermore, to assess the vessel response it is also necessary to know the exact shape of the dynamic pressure peak (rising pressure time during the flame propagation and peak duration) because the final stress state in the wall is also determined by the dynamic amplification factor which may reach a maximum of two when the rising time is much shorter and the peak duration is greater than the natural period of the shell expansion mode. It has been consevatively assumed a rising time negligible with respect to the radial vibration period that for the structure under consideration is about 20 msec, as well as a peak duration comparatively long. Consequently a factor of 2 has been applied to the static peak pressure. Therefore the used model is not completely consistent and further studies will be performed to clarify this problem.
The other loads considered are:
- the weight of the containment vessel,
- the weight of the polar crane, which was considered as an uniform load along the circumference.

RESULTS

The main results of the overall collapse analysis are shown in FIGs. 8 through 11.
Tab. 1 presents the maximum equivalent strain and stress vs. Δp.

TAB.1

Node	Step	Δp (MPa)	$\varepsilon_{equiv.}$	$\sigma_{equiv.}$ (MPa)
82-110	27	0.740	1.521e-02	295
82-110	30	0.800	5.069e-02	318.5

The cumulated strains are about 5% in the most unfavourable case. The maximum differential pressure achieved was Δp = 0.8 MPa; in this situation a wide plastic flow was obtained as pointed out in FIGs. 10-11, where the deformed profiles of the containment vessel are shown. The maximum stresses obtained are shown in tab. 2.
As shown in table 2, the maximum equivalent Von Mises stress is everywhere below the flow stress value (σf = 383.7 MPa), which is assumed as collapse strength.

TAB.2

Node	Step	Δp (MPa)	$\sigma_{equiv.}$ (MPa)
110	1	0.378	158.4
52-82/110-128/154-164	15	0.500	208
52-82/110-128/154-164	20	0.600	248
52-82/110-128/154-164	25	0.700	286
72-122	27	0.740	295
77-110	30	0.800	318.5

From these results it is possible to affirm that the plastic collapse cannot occur until a differential pressure of Δp = 0.8 MPa is reached. At that condition the maximum radial displacement of the shell, obtained by MARC code, is 87.7 cm (node 85); however the maximum radial displacement of the polar crane ring is 2.12 cm and it is only of thermal nature because the stiffness of the ring is large compared with the shell one. The thermal elongation of the polar crane beams is of the same order of magnitude of that of the ring and this prevents the polar crane from falling.
The collapse by the vertical dead weight loads is prevented; also without the stiffening contribution of the pressure, supposed to fall after the venting, o the opening of the relief valves or a through-wall crack.
The vertical buckling, in the worst deformed configuration, is 44.4 times the dead weight
The local analysis of the penetration yields a confined plasticity at a differential pressure, Δp, of 0.60 MPa.
This plastic flow, localized at the upper side, extends with increasing Δp reaching a maximum value of 0.104 m/m at Δp = 0.760 MPa with a peak stress of 354 MPa close to the flow stress of the material. A frontal and a lateral view of the penetration, with isostress lines represented at Δp = 0.760 MPa, are shown in Figs. 12-13.

FRACTURE MECHANICS CONSIDERATIONS

The impact of a possible crack on the integrity of the structure has been analyzed.
A conservative approach has been used assuming that the cack extends continuously all over the circumference in the most stressed region i.e. at

the base, and the material performs elastically with a toughness KIC ranging between 80 and 120 MPa√m.
Details of the analysis can be found in G. Maresca, P.P. Milella, G. Pino '88. The results are shown in FIG. 14. As it can be seen the applied stress intensity factor, Ki, at the peak pressure crosses the domain of the critical Kic for a crack depth ratio to the containment thickness, a/t, greater than 0.35.
Any crack of the lower depth would not jeopardize the integrity of the containment vessel. It is unlikely that cracks of such an extension either exist or escape a nondestructive examination.
A particolar attention should be given to the penetration area with higher local stress and thickness. An analysis of crack behaviour in that region shall be performed to role out the possibility of a premature failure.

BUCKLING FROM THE EXTERNAL LOADS

In order to reduce the internal temperature and, therefore, the overpressurization of the containment vessel, a possible solution is the the external flooding of the shield building annulus above the piping penetrations region. In this case the possibility of buckling induced by external hydrostatic pressure arises (G. Maresca, P.P. Milella, G. Pino, '87).
For this purpose a calculation, with INCA computer code, was performed, to evaluate the maximum height that a water column can reach without a prejudice for the safety. Assuming a safety factor of 2 on the water column height, a safe value of 5 m was found for this parameter.

CONCLUSIONS

In conclusion, from the analysis of the considered rupture modes it is possible to affirm that:
- the plastic collapse of the overall structure cannot occur until the the differential pressure Δp = 0.8 MPa is passed,
- the local failure in the penetration area, without any existing crack, cannot occur until the differential pressure Δp = 0.76 MPa is passed, differential pressure Δp = 0.76 MPa is passed,
- the fall of the polar crane, following a large deformation of the shell, does not occur because the radial displacement of the polar crane ring is of the same order of magnitude of that of the polar crane beams,
- the collapse from the vertical loads is prevented because the strength of the deformed structure in plastic field is still enough to avoid the collapse, following the venting of the pressure,
- the crack propagation is unlikely to occur with a depth of the flaw less than 30% of the thickness,
- The buckling of the shell, with the external hydrostatic loads following a external spray cooling, is impossible to occur with a water column height less than 5 m.

REFERENCES

J.H. Gittus " PWR Degraded Core Analysis ". Nuclear Power Development Lab., Springfields, April '82.
G. Maresca, P.P. Milella, G. Pino " Ultimate strength and rupture modes for metal containment system type MARK III under pressure load ". International ENS/ANS Conference on Thermal Reactor Safety, Avignon, October '88.
G. Maresca, P.P. Milella, G. Pino " Measures of heat removal from the containment vessel of Alto Lazio NPP ". ENEA DISP ACO ATEM report, Rome, December '87.

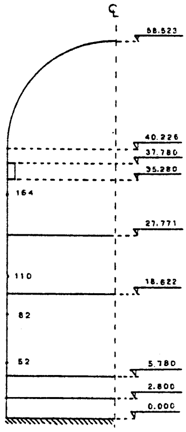


FIG.1
Simplified sketch of the containment model.

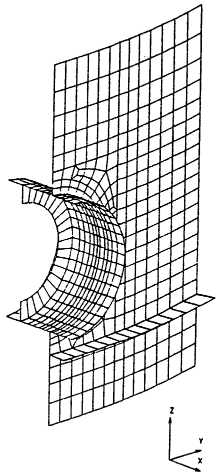


FIG.2
The personnell hatch penetration 3-D model.

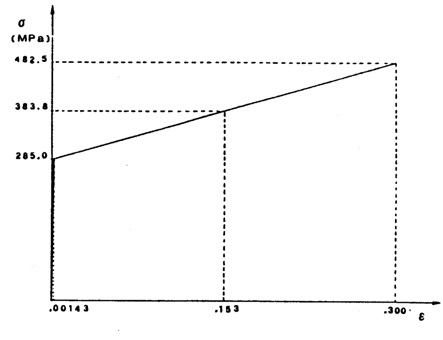


FIG.3
Bilinear stress-strain relationship adopted.

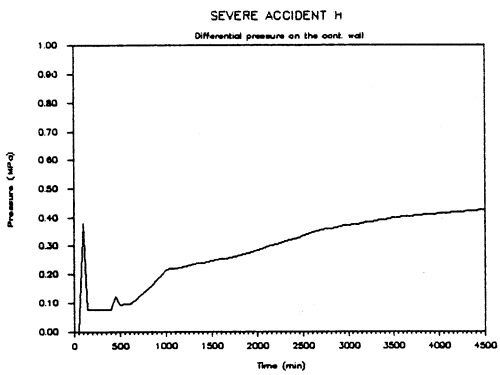


FIG.4
Pressure transient as a consequence of the considered severe accident.

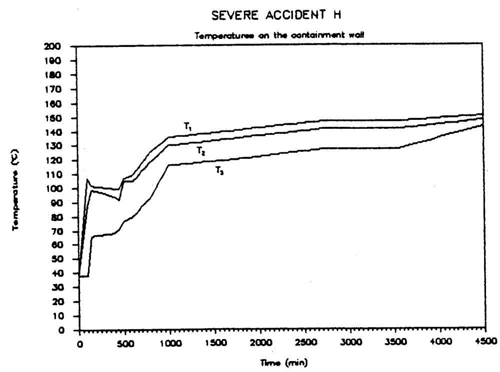


FIG.5
Temperature transients on zone 1, 2 and 3 of the inside wall.

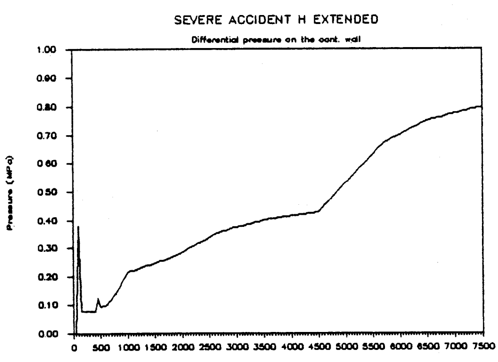


FIG.6
The extended transient. Differential pressure is rised up to 0.8 MPa.

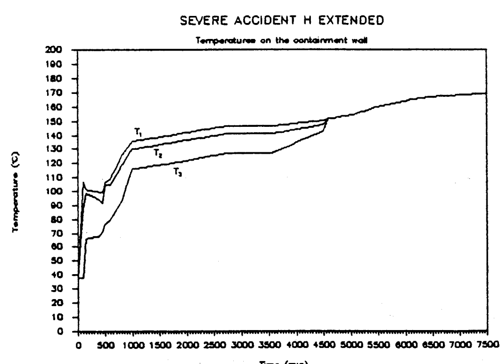


FIG.7
The extended transient. Temperature in zone 1, 2 and 3 is the same.

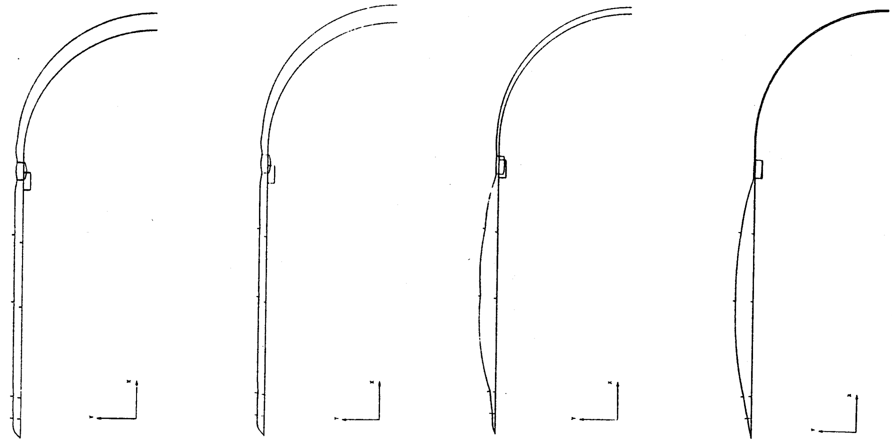
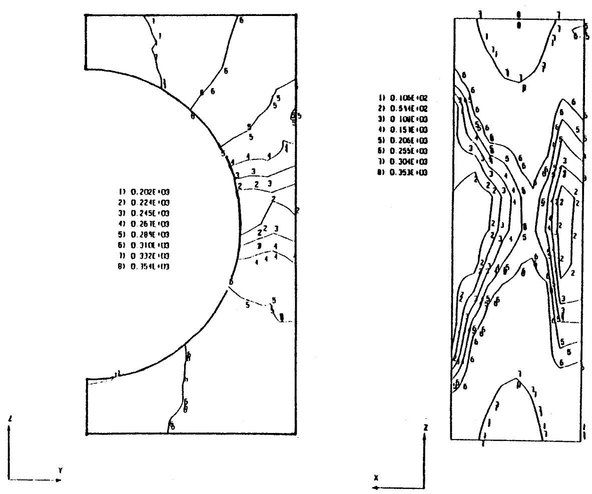


FIG.s 8-9-10-11
Deformed and undeformed shapes of the containment vessel at pressure steps 15 (▲p = 0.50MPa), 25 (▲p = 0.70MPa), 27 (▲p = 0.74MPa) and 30 (▲p = 0.80MPa).



FIGs. 12-13
Isostress lines in the personnell hatch penetration. Frontal and lateral view.

FIG.14
Trend of the Stress Intensity Factor KI for a continuous crack as function of the crack depth to containment thickness ratio, a/t. Unstable propagation can occurr when KI reaches the thoughness of the material, KIc, assumed to range from 80 to 120.