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Analysis of a Fast Breeder Reactor Building on Classical Foundations in Highly Seismic Sites

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SUMMARY

The structural design of a Pool-type Fast Breeder Power Plant in sites of high seismic activity is presently developed in France. Foundations on sliding pads are devised to account for a reduction of the base acceleration. On the other hand, in Italy, the National Nuclear Energy Commitee (ENEA) has recently promoted a feasibility analysis of a similar plant on classical foundations.

In the present paper the structural design of the reactor building is considered under an earthquake excitation defined by USNRC R.G. 1.60, normalized to 0.3g.

The feasibility of the building for variable soil properties, as required for the so-called "unified-project", is verified, and, on these premises, the design is directed towards:

1) a minimization of the excitation transmitted to the reactor assembly,
2) the optimization of the civil works.

The variability of soil properties is defined by three different property sets:

a) hard soil, E = 80000 Kg/cm^2, φ = 45°, ν = .40,
b) medium soil, E = 20000 Kg/cm^2, φ = 37°, ν = .40,
c) soft soil, E = 5000 Kg/cm^2, φ = 35°, ν = .45,

where: E = Young's modulus,
φ = friction angle,
ν = Poisson's ratio.

The design optimization analyzes the following parameters:

1) building embedment,
2) connection between reactor containment and building structures,
3) mat stiffening,
4) thickening of the reactor containment walls.

An economical comparison between the considered solutions, estimating the total volume of concrete, the average steel reinforcement and the volume of excavation is presented.

The results show that an embedment of the building of 20m is to be recommended in order to reduce the seismic response of the reactor assembly, while economical considerations would direct the choice towards a moderate embedment, of about 11m depth.

Moreover, the analysis points out that the top of the reactor containment should be conveniently linked to the building main structure and that a stiffer mat is generally to be preferred .

However, the influence of the site characteristics on the dynamic behavior of the whole structure is not to be neglected. For this reason, guidelines are provided also for the choice of a solution suitable to any of the three sets of soil properties.

1 INTRODUCTION

The reactor building layout has a rectangular plan 62m wide and 80m long, and a height of 69m.

It consists of two main lateral bodies running all over the longitudinal axis of the building at each side of the reactor.

The central nave contains the reactor at its centre and auxiliary rooms, such as the fuel storage, on the sides. It is surmonted by a dome, housing the fuel handling system actuators. To allow fuel handling movements, the building has no resistant slabs above the reactor roof one, at elevation 20m.

The reactor assembly, whose main technical options are the use of sodium as a cooler and a "pool" design (consisting in the whole primary circuit in a single vessel), is suspended from the top of a cylindrical concrete ring of 1.80m in thickness, supported by the reactor concrete mat. This ring will be henceforward referred to as "reactor containment"

The building original, or reference, solution has wall thicknesses of 1m-except for the antimissile walls, which are 1.20m thick-and a mat thickness of about 3m. For this solution the top of the reactor containment is not connected to the adjacent building slabs.

2. MODELLING OF THE BUILDING

The reactor building feasibility has been investigated through a two-phase approach:

a) in the first phase, the seismic loads have been evaluated all over the building and in the adjacent soil through the dynamic analysis of a FLUSH model (ref. 1) of about 900 degrees of freedom. The soil structure interaction has been taken into account according to the state-of-the-art rules in this field;

b) in the second phase, the seismic loads previously evaluated have been considered together with static and thermal loads, in order to carry out the static analysis of the building.

   The model used in the analysis, shown by fig.4, consists of as many as 7,000 nodes and 11,000 elements and has about 21,500 degrees of freedom.

   The box-type nature of the building has allowed the use of plate elements for the reactor mat, the reactor containment concrete walls and the external embedded walls. All other walls and slabs have been represented by membrane elements.

3. OUTLINES OF THE BUILDING DYNAMIC ANALYSIS

The influence of the most important parameters considered in the analysis is investigated through the accelerations and the floor response spectra calculated at the top of the reactor containment, in the case of a transversal excitation.

3.1 Soil property influence

The influence of soil properties on the floor response spectra obtained at the top of the reactor containment is shown in fig. 1b, 1c, 1d. The pseudo-acceleration at this point is reported versus frequency, for each of the main structural solutions considered, for a 20m embedment and for each of the three soil properties taken into account. The damping ratio is 4%, a value fitting the high earthquake intensity (0.3 g). It can be easily noticed that for any embedded solution the envelope spectrum is essentially coincident with the one pertaining to the hard soil, whereas for non embedded solutions the soft soil provides the most severe condition in the low frequency zone of the spectrum (see fig. 1.a, showing the results obtained for the building reference solution).

From the point of view of the building response, as well, the maximum accelerations are generally obtained in the case of a hard soil, as shown in the profiles of fig. 2a, 2b.

3.2 Embedment effect

The effect of embedment on the seismic response at the top of the reactor containment is shown in table II and in fig. 1e. The values of (a^*) reported in tab. II correspond to the acceleration evaluated at this point due to the rigid body motion of the building alone, and show that the embedment effectiveness is of primary importance. No further effect, though, is found for hard soils when passing from an 11m to a 20m embedment. The evaluation was carried out for the building reference solution; in the case of a horizontally restrained solution, the floor response spectra reported by fig. 1e show that the previous conclusion is still essentially valid, even if further gain is obtained for a 20m embedment.

Another phenomenon which can be remarked is the shifting of the peak frequencies of the spectra towards the high frequency zone, as the depth of embdment is increased. This fact can be intuitively explained observing that the envelope spectra reported correspond, practically, to a hard soil situation.

From the point of view of the building behavior, the effect of embedment can be estimated by means of the building acceleration profiles reported by fig. 2a, 2b. It is evident that none of the depths of embedment considered is sufficient to reduce the accelerations induced in the upper part of the building in a significant amount. Stiffening and strengthening of the dome terminal walls seem therefore to be required in any case: however, the low acceleration values evaluated up to 31m of elevation seem to indicate the case of a 20m embedment as the most satisfactory, after an intervention of the above-mentioned type.

3.3 Effect of the building structural solution

The effect of the choice of different structural solutions on the reactor assembly seismic response can be estimated by fig. 1.f, where the floor response spectra at the top of the reactor containment for the solution types F (reference building), B (stiffened mat) and I (reactor containment horizontally restrained) are compared in the case of a 20m embedment. In accordance with the conclusions of par. 3.2, this comparison shows that a stiffer structural solution results in a simultaneous reduction and shifting to high frequencies of the peaks in the spectra. However, stiffening the mat appears less advantageous than the linking the reactor containment and the building structures, at least in the frequency range interesting the reactor assembly response (2-10 Hz). The benefit of a horizontal restraint between reactor containment and building, in terms of acceleration at the top of the reactor containment is shown in tab. 2, which also shows that embedded solutions only benefit by a stiffer mat. From the point of view of the building response, it can be observed (fig. 2a, 2b) that a 20m embedment prevents the increase of acceleration in the upper part of the building, experienced to some extent by the horizontally restrained solution without embedment, and, in the case of hard soils, also for an 11m embedment.

3.4 Contributions to the reactor assembly response

Table I shows different contributions to the horizontal acceleration at the top of the reactor containment, for the reference building solution. The assumption on which such splitting has been carried out is not rigorously true (which explains the negative value found in the table), however, it allows a significant insight into the problem.

The most effective factors, with regard to the excitation transmitted to the reactor assembly, appear to be, in the order of importance:

1) the building translational movement,
2) the deformability of the reactor containment walls,
3) the deformability of the reactor containment mat.

Such results point out the primary importance of the embedment (acting on the building response at the mat level). The importance of a linkage between reactor containment and the adjacent slabs of the building, resulting in a limitation of the deformability of the reactor containment walls, is also explained, as well as the secondary influence of a mat stiffening.

4. BUILDING FEASIBILITY

The building feasibility has been verified for the solution transmitting the minimum excitation to the reactor assembly, namely, a solution presenting a 20m embedment and the top of the reactor containment connected to the adjacent building slabs.

The first approach phase of the feasibility analysis has shown that only minor modifications of the reference building are required: the introduction of supplementary transversal walls, the thickening of the reactor mat and of some external walls.

Apart from that, the building feasibility is verified without any further increase in the wall thicknesses and within the limit of 200 Kg/m^3 as regards the amount of steel reinforcement. A supplementary analysis is necessary only for the dome transversal walls, for which the need of an increased stiffness is confirmed. An evaluation of the amount of steel reinforcement required for the main building structures has been carried out on the basis of the ACI 318 recommendations (ref. 3).

With respect to the problem of soil bearing capacity, in the main assumption of a water table 5m below the ground level, we can observe that the embedment has three different kinds of effect: two of them are favorable, one is unfavorable. The favorable effects are:

1) the lateral earth pressure, which partly counterbalances the seismic loads,
2) the overload due to the adjacent soil, stabilizing to some extent the soil under the foundation.

On the contrary, the buoyancy due to the water table under the building has a destabilizing effect. The main result is that the stability factor, as evaluated according to Hansen's method (ref. 2), is not sufficiently high for a non-embedded building, its maximum being reached for a depth of embedment of about 11m.

Lastly, the problem of the feasibility of the horizontal restraint between the top of the reactor containment and the building structures, required to ensure a good dynamic behavior of the reactor assembly, has been investigated. A practical realization of the connection, using Teflon sliding pads, which show good safety and durability characteristics, is illustrated in fig. 3.

5. ECONOMICAL COMPARISON AMONG DIFFERENT BUILDING SOLUTIONS.

As a conclusive issue of the present investigation, an attempt is made to draw a comparison from the economical point of view among the most significant building solutions. The parameters chosen to give an account of the cost of each solution are:

a) the volume of concrete,

b) the average amount of steel reinforcement,

c) the estimated volume of excavation.

Each of these parameters has been evaluated for the "unified-project" horizontally restrained solution in the case of 11m or 20m embedment. The same evaluation has been carried out for a building solution taking into account only selected soils, namely medium or soft ones. The results of these estimations are reported in table III, where a similar evaluation is also provided for the building reference solution, as a term of comparison: an easily predictable increase in the costs is presented by each feasible solution for a 0.3g design earthquake if related to the reference building design for 0.15g, but this increase can be limited in the case of a moderately embedded solution. Moreover, these results point out the interest of standardization: in fact, a building scheme adapted to soft soils only would bring about a cost reduction of no more than 10% with respect to a unified design valid for variable soil properties.

The data in table III are indicative as well for an overall economical analysis involving also the seismic design of the reactor assembly.

6. CONCLUSIONS

It may be concluded that for a design earthquake of 0.3g, only minor modifications of the reference building and an amount of steel reinforcement below 200 Kg/m^3 are required to ensure the feasibility of the reactor building.

An embedment of 20m of the building, with a horizontal restraint between the top of the reactor containment and the adjacent building slabs allows to reduce significantly the seismic excitation transmitted to the reactor assembly. However, the solution, that the present investigation has pointed out as the most favorable as to the overall cost, is the one with an embedment of about 11m. Such a solution requires further investigation in the dynamic behavior of the upper part of the building, for which stiffening appears advisable. Attention should be devoted as well to the dynamic response of the most important reactor components, showing a great sensibility towards any intervention affecting the seismic excitation transmitted through the building.

7. ACKNOWLEDGEMENTS

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TAB. I - Estimation of the percent contributions of the main parameters to the transversal acceleration at the top of the reactor containment according to FLUSH results for the reference solution.

E_{soil}/embedment (10^3 kg/cm^2)/(m)	80/0	80/11	80/20	20/0	20/11	20/20	5/0	5/11	5/20
Building translation $A^2_{mat}/A^2_d \times 100$	48%	43%	48%	33%	51%	58%	60%	69%	68%
Building rocking $A^2_{rock}/A^2_d \times 100$	2%	1%	2%	14%	4%	2%	9%	9%	7%
Mat deformability $A^2_{mat\ def.}/A^2_d \times 100$	22%	39%	13%	6%	8%	11%	7%	11%	28%
React.contain.def. $A^2_{rw\ def.}/A^2_d \times 100$	28%	17%	37%	47%	37%	29%	24%	11%	-3%

A_{mat} = building transversal acceleration at the mat level

A_d = transversal acceleration at the top of the reactor containment

$A_{rock.}$ = transversal acceleration at the top of the reactor containment due to the building rocking movement $A_{rot,mat.} \times h_{rw}$ where:

$A_{rot,mat}$ = Rotational building acceleration at the level mat

h_{rw} = reactor containment height

$A_{mat\ def.}$ = transversal acceleration at the top of the reactor containment due to mat deformability

$A^2_{mat\ def.} = A^2_{rot,rw} - A^2_{rock}$

$A_{rot,rw}$ = transversal acceleration at the top of the reactor containment due to rotation at the base

$A_{rw\ def.}$ = transversal acceleration at the top of the reactor containment due to deformability of containment walls

$A^2_{rw\ def.} = A^2_d - A^2_{rot,rw} - A^2_{mat}$

TAB. II - Evaluation of the effectiveness of the main parameters according to FLUSH dynamic results.

E_{soil}/emb. 10^3 kg/cm^2/m	a^* (g)	$\eta_e = a_o^*/a^*$	a_F (g)	a_I (g)	$\eta_I = a_F/a_I$	$K = a_I/a^*$	a_B (g)	$\eta_s = a_F/a_B$
80/0	.4086	1	.5780	.4871	1.19	1.19	.9021	0.64
80/11	.2655	1.54	.3990	.3242	1.23	1.22	.3483	1.15
80/20	.2656	1.54	.3739	.3064	1.22	1.15	.3311	1.13
20/0	.3615	1	.5298	.4414	1.20	1.22	.7471	0.71
20/11	.2585	1.40	.3457	.2996	1.15	1.16	.3288	1.05
20/20	.2373	1.52	.3055	.2815	1.09	1.19	.3049	1.00
5/0	.3122	1	.3766				.3525	1.07
5/11	.2304	1.36	.2610	.2215	1.18	0.96	.2421	1.08
5/20	.1994	1.57	.2304	.2174	1.06	1.09	.2411	0.96

a^* = maximum acceleration at the top of the reactor containment in the case of infinite stiffness of mat and reactor containment for the reference solution

η_e = embedment effectiveness

a_o^* = maximum acceleration at the top of the reactor containment for the reference solution

a_I = maximum acceleration at the top of the reactor containment for the horizontally restrained solution

η_I = effectiveness of the linkage between the top of the reactor containment and the building adjacent walls (horizontal restraint)

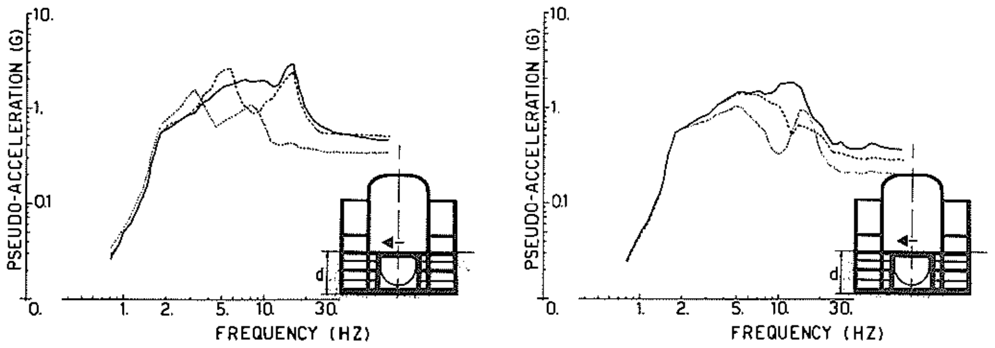
k = relative effectiveness of an infinite stiffness of mat and reactor containment walls to the horizontal restraint

a_B = maximum acceleration at the top of the reactor containment for a solution with stiffened mat

η_s = effectiveness of the mat stiffening

TAB. III - Parametric evaluation for different building solutions from the economical point of view.

Different building solutions	Concrete vol. (m^3)	Aver. steel reinf. (Kg/m^3)	Excavation (m^3)	Steel mat reinf. (Kg/m^3)	Main walls reinf. (Kg/m^3)
Unified solution for three different soils-20 m embedment design earthquake 0.3 g	85,000	150	130,000	140	170
Unified solution for three different soils-11 m embedment design earthquake 0.3 g	85,000	145	80,000	135	160
Building solution for medium soil-20 m embedment design earthquake 0.3 g	82,000	140	130,000	115	155
Building solution for soft soil-20 m embedment design earthquake 0.3 g	81,000	135	130,000	105	145
Building solution for medium soil-11 m embedment design earthquake 0.3 g	81,000	135	80,000	115	150
Building solution for soft soil-11 m embedment design earthquake 0.3 g	80,000	130	80,000	105	140
Reference solution without embedment design earthquake 0.15 g	76,000	130	25,000	130	140

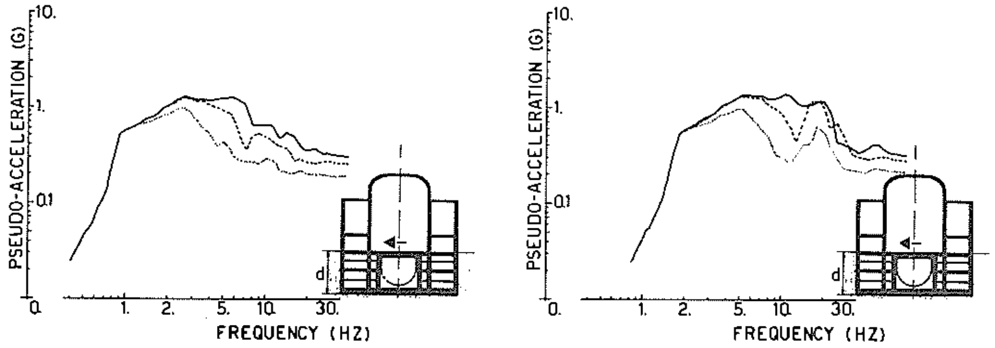


a. Reference solution d = 0m

···· E_{soil} = 5000 Kg/cm^2
-- E_{soil} = 20000 kg/cm^2
— E_{soil} = 80000 Kg/cm^2

b. Reference solution d = 20m

···· E_{soil} = 5000 Kg/cm^2
-- E_{soil} = 20000 Kg/cm^2
— E_{soil} = 80000 Kg/cm^2

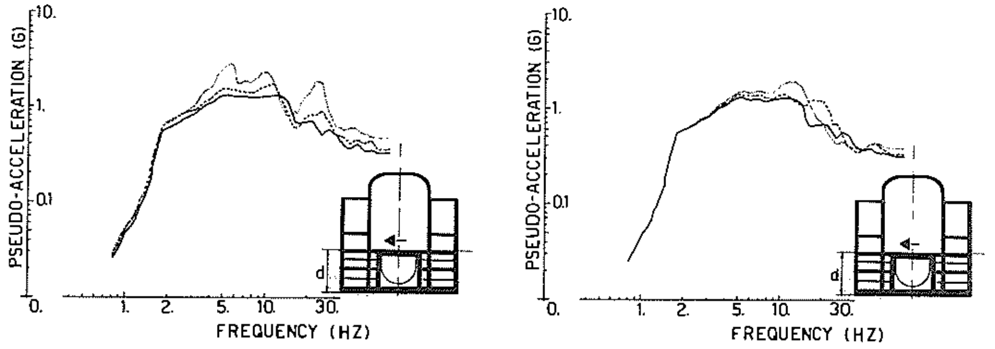


c. Reactor containment horiz. restrained d=20m

···· E_{soil} = 5000 Kg/cm^2
-- E_{soil} = 20000 Kg/cm^2
— E_{soil} = 80000 Kg/cm^2

d. Stiffened mat d = 20m

···· E_{soil} = 5000 Kg/cm^2
-- E_{soil} = 20000 Kg/cm^2
— E_{soil} = 80000 Kg/cm^2



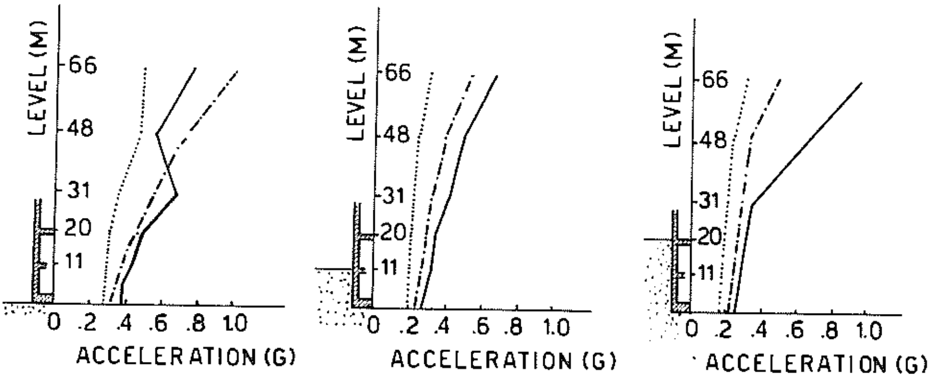
e. Reactor containment horizontally restrained (envelope f.r.s.)

--- d = 0m
-- d = 11m
— d = 20m

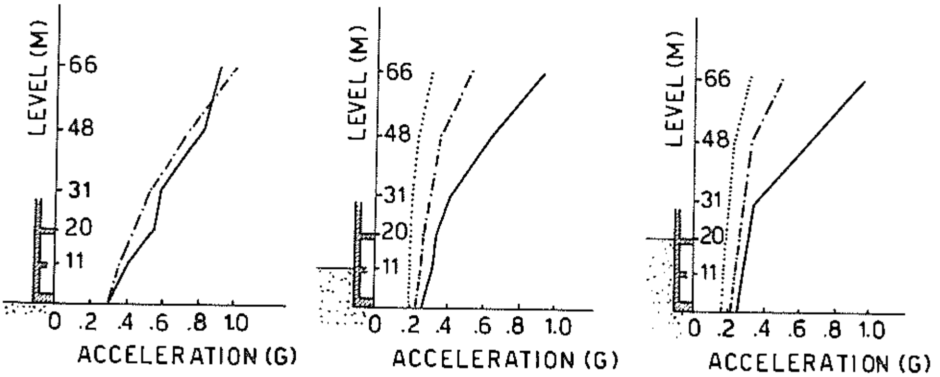
f. 20m embedment solutions (envelope f.r.s.)

···· reference solution (F)
-- stiffened mat (B)
— reactor containment horizontally restrained (I)

Fig. 1 - Transversal floor response spectra at the top of the reactor containment (level 20m).



a. Reference solution



b. Reactor containment horizontally restrained

Fig. 2- Transversal acceleration profile along the reactor axis for different depths of embedment (FLUSH results).

······ E_{soil} = 5000 Kg/cm^2
-·- E_{soil} = 20000 Kg/cm^2
— E_{soil} = 80000 Kg/cm^2

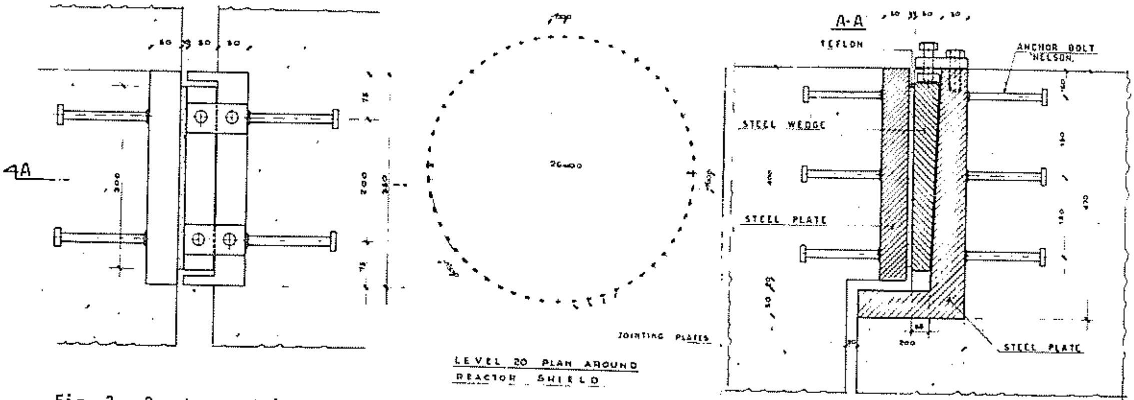
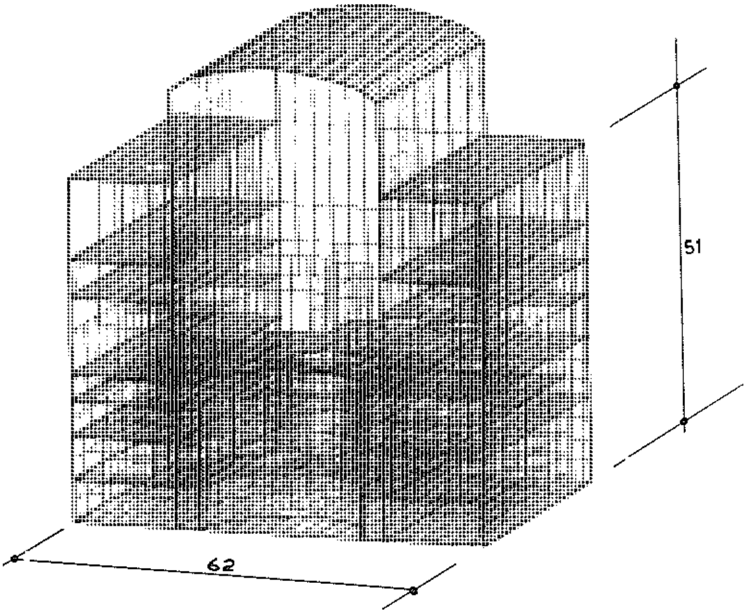
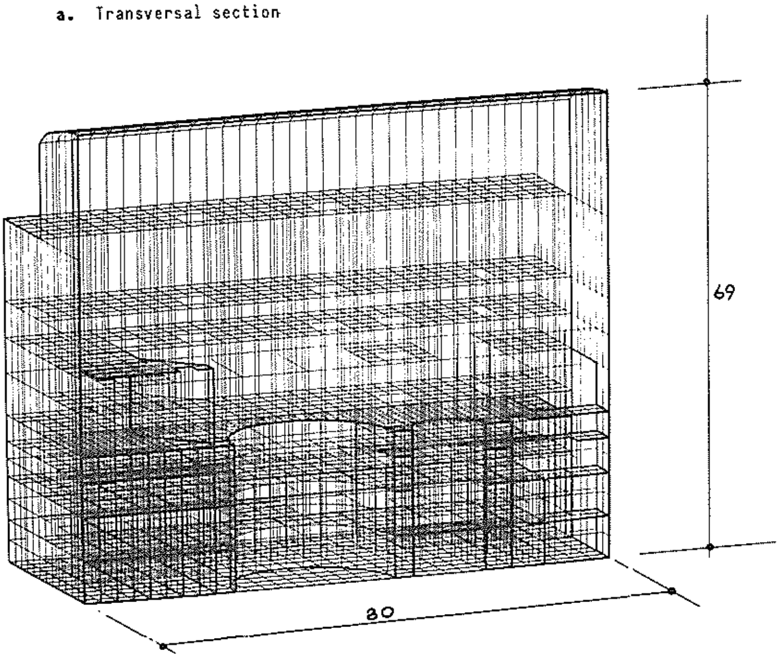


Fig. 3 - Reactor containment - building connection: proposed solution making use of Teflon pads.



a. Transversal section



b. Longitudinal section

Fig. 4 - Building static model: perspective views.