18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-B02-5

STRUCTURAL ANALYSIS OF RRRP REFLECTOR VESSEL

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ABSTRACT

This paper presents the main features of the design and structural analysis of the Reflector Vessel (RVE) for the RRRP. The RRRP is a 20 MW multi-purpose nuclear research reactor designed and constructed by INVAP from Argentina, for the Australian Nuclear Science and Technology Organization (ANSTO). The reactor core is surrounded by the RVE which is filled with heavy water and serves several functions.

The successful performance of the RVE is paramount to the success of the RRR project. Its design has meant a large engineering effort that involved a close interaction between structural analysis, neutronic calculations, thermal, hydraulics, material science, and manufacturing and assembly demands.

The present report describes the main steps followed in the process of development of the RVE, including design, calculation, RVE mock-up manufacturing, vessel and chimney final construction and testing. Main features of the structural analysis performed are presented, including load cases, their classification and requirements. Pressure and temperature corresponding to normal operation, design load and special situations such as second shutdown system operation, seismic event, irradiation-induced Zircalloy growth, were taken into account.

Stresses, displacements and buckling factors are calculated according to requirements and applicable standards, under normal and accidental conditions.

Keywords: finite element, models, reflector vessel, RRRP

1. INTRODUCTION

The RRRP (Replacement Research Reactor Project) is a 20 MW multi-purpose nuclear research reactor designed and constructed by INVAP from Argentina, for the Australian Nuclear Science and Technology Organisation (ANSTO). The reactor is being constructed at a location near Sydney. The reactor objectives are to provide radioisotopes and extensive neutron beam research capabilities.

The reactor core is surrounded by the RVE which is filled with heavy water and serves several functions:

a) It enhances the neutronic performance of the core by reflecting neutrons;
b) It provides a large volume with elevated neutron fluxes to place targets for radioisotope production and extract several neutron beams; and
c) By draining the heavy water it serves as a second shutdown system for the reactor.

The Reflector Vessel (RVE) is a complex technological component of key importance for the RRRP as it integrates the core, the reactivity control features and the reactor utilization is built around it. The successful performance of the RVE is paramount to the success of the RRR project.

The vessel is a cylindrical tank 2.6m in diameter, 1.2m high. It is made of Zircalloy and filled with heavy water, except for the central chimney (filled with light water), which hosts the core. The RVE includes many passing tubes to allow for the cooling of the core, the use of neutronic beams, the irradiation of Silicons and radioisotope targets, the operation of a cold neutron source and a hot neutron source, pneumatic lines and bulk rigs, among others. Its design has meant a large engineering effort that involved a close interaction between structural analysis, neutronic calculations, thermal, hydraulics, material science, and manufacturing and assembly demands. This implies the simultaneous fulfillment of frequently conflicting requirements concerning materials, wall thickness, facility locations, welding attributes, tolerances, etc.

The present paper describes the structural analysis of the RVE, as well as it provides some information on the main steps followed in the process of development of the RVE (design, calculation, mock-up and final manufacturing, tests). The objective of this work is to verify the RVE structure, including its central chimney. It is presented the main features of the structural analysis performed, the finite element models employed for design review and verification and the handling of the different load cases (design load, normal operation and abnormal conditions) and boundary restrictions. Two main models were developed:

a) Global RVE model: includes the vessel envelope, central chimney, cold and hot neutron sources, neutron beams, several irradiation positions, structural columns and main openings, as well as the RVE supporting structure, in order to better simulate the boundary condition. Model A allow as to obtain the global behavior of the structure;
b) Chimney model: Detailed model to obtain more accurate local loads and determine the acceptability of specific design features.

Additional sub-models were developed to analyze the structural behavior of the beams and other parts.

The structural analysis envelops all the load cases, including the following loads: pressure and temperature corresponding to normal operation, design load and special situations such as second shutdown system operation, seismic event, irradiation-induced Zircalloy growth, and loads arising from manufacturing and assembly tolerances. Separated assessments of special loads –such as effects of cold neutron source explosion on RVE internals, or impacts from falling objects- were also performed.

2. INPUT DATA

2.1 General geometry

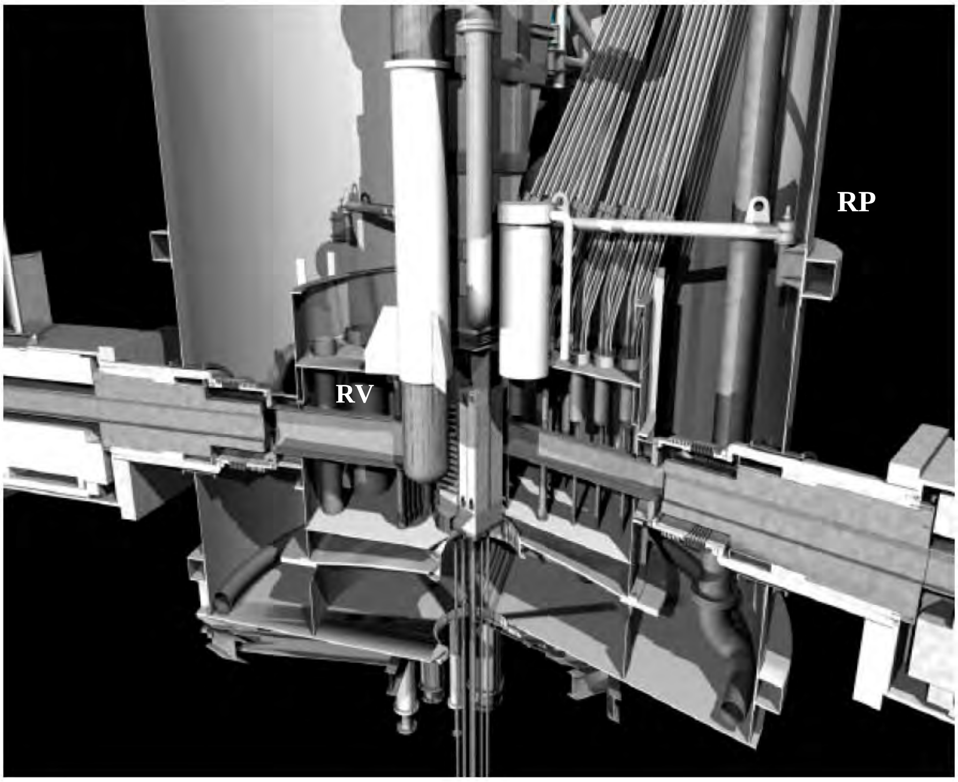


Figure 1 - View of the reflector vessel location inside reactor pool

Reflector Vessel (RVE) has a circular shape, with two plane heads. It comprises several columns (“I” cross section) between both heads to homogenize loads and avoid excessive strains, displacements, and stresses when pressure loads are applied. Some pass-through irradiation columns (such as FP y Si) behave also as structural columns, because they join both vessel heads and are stiff enough.

Figure 1 shows a cross-section of the reactor pool (RPO), including specific labeling of the pool external wall (label “RP”) and the reflector vessel (label “RV” located under the vessel top head, over one neutron beam).

The chimney –which hosts the core- can be seen in RVE central zone. The control plates guiding can be seen below the core. Some irradiation connections on the RVE top head are also shown.

Figure 2 shows the general assembly of RVE, main global dimensions, and main features such as cold and hot neutron sources, neutron beams, and main openings carrying heavy water to and from RVE.

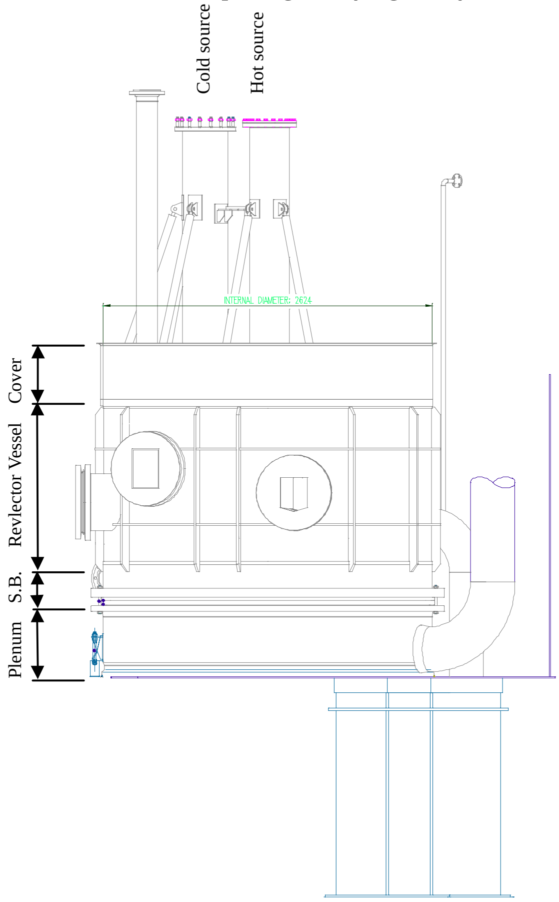


Figure 2 - Cross section and lateral view of the general assembly of the reflector vessel

Right side of Figure 2 shows a lateral view of reflector vessel. Attached structures are also shown. These structures have been included in the models in order to more accurately represent the interaction between them and RVE: top cover, cold and hot neutron sources, suction box and plenum, among them.

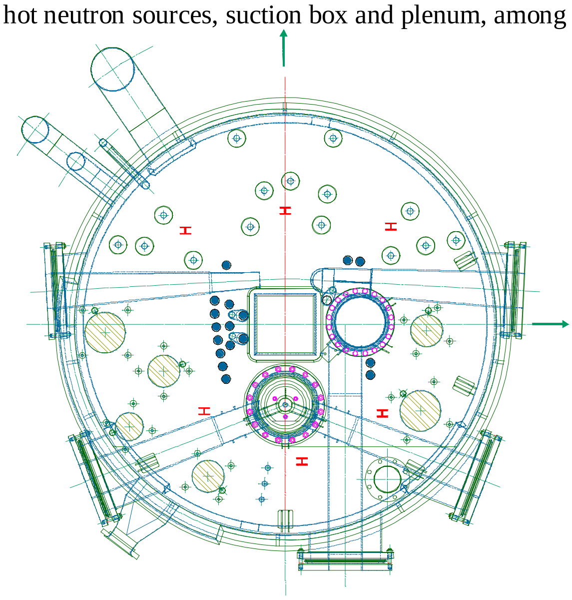


Figure 3 - RVE top view

Figure 3 shows a top view of the RVE, including central chimney, holes for neutron sources, pass-through irradiation columns (dark dots), silicons (light slanted lines) and position for structural columns ("I" marks) between top and bottom heads inside reflector vessel.

Figure 4 shows a sketch of central chimney. It can be seen its central wall, with reinforcements –which allow structural stiffening as well as thermal dissipation, and span approximately the active core height.

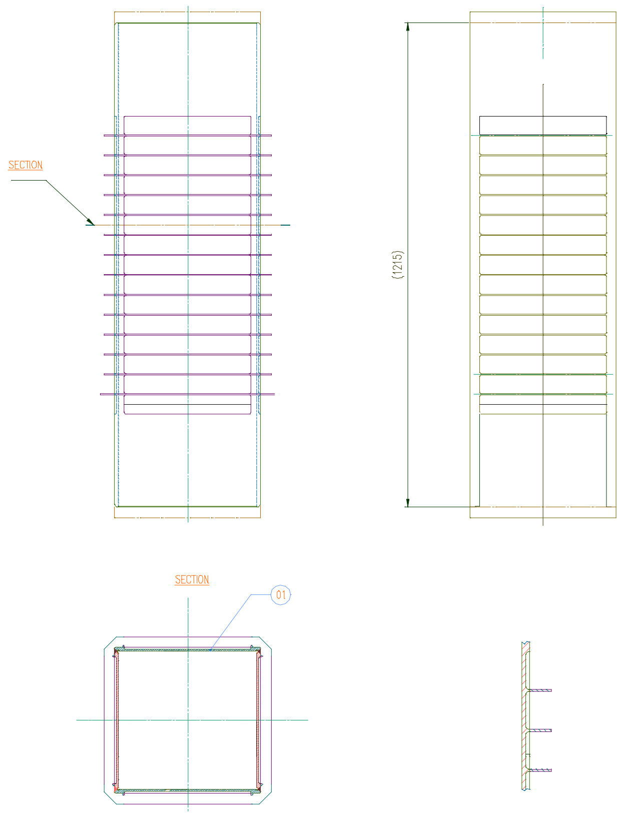


Figure 4 – Central chimney sketch

2.2 Material properties

Properties of the main structural materials used in the model were taken from ASTM, ASME and other standards. There are three Zircaloy alloys and stainless steel (A-240 304L) involved in the design.

Allowable stress were calculated according to ASME Boiler & Pressure Vessel(i) standard, for plate elements, levels A and B. (Zircaloy: Service level A: $\sigma m \leq 110$ MPa; (σm or σL) + $\sigma b \leq 165$ MPa; Level B: $\sigma m \leq 121$ MPa; (σm ó σL) + $\sigma b \leq 181.5$ MPa; where σm is the membrane stress, σb is the bending stress and σL is the local membrane stress, which includes discontinuity effects; all are normal maximum).

2.3 Load cases

The following load conditions are considered:

a) Pressure loads (document [8])
   - (i) Normal operation pressure
   - (ii) Design pressure
   - (iii) Pressure during Commissioning Heavy Water Filling and Heavy Water Replacement
   - (iv) Pressure during Second Shutdown System action with primary cooling system in operation
   - (v) Overpressure in Cover gas

b) Temperature
   - (i) Normal operation temperatures
   - (ii) Second Shutdown System action temperatures

c) Growth of Zircaloy due to irradiation exposure (documents [8] and [9])

d) Seismic event (document [10])

e) Own weight of the components and its normal contents under operating conditions (taken into account in every combined load case)

Analyses on model are considered for the following load cases shown in Table 1.

Load case number	Name	Individual Load Cases										Service Level	Comments
		Pressure Normal Operation	Temperature Normal Operation	Pressure Design Load	Pressure Heavy Water Replacement	Pressure SSS Action	Temperature SSS Action	Overpressure Cover Gas	Zircaloy Growth 40 years	Seismic Event	Own Weight		
		a-i	b-i	a-ii	a-iii	a-iv	b-ii	a-v	c	d	e		
1	Normal operation	X	X	-	-	-	-	-	X	-	X	A	Done
2	SSS Action and primary CS	-	-	-	-	X	X	-	X	-	X	B	Covered by 6
3	Heavy Water Replacement	-	-	-	X	-	-	-	X	-	X	A	Covered by 6
4	Íd. 2 and seismic event	-	-	-	-	X	X	-	X	X	X	B	Covered by 7
5	Overpressure Cover Gas	-	X	-	-	-	-	X	X	-	X	B	Covered by 6
6	Design Load case	-	-	X	-	-	X	-	X	-	X	B	Done
7	Id. 6 and seismic event	-	-	X	-	-	X	-	X	X	X	B	Done

Table 1 – Final combined load cases

Of the 7 cases, only combined load cases number 1, 6 and 7 are analyzed. These load cases represent the normal operation load and the worst cases global loads (maximum pressures and thermal gradients). Seismic event load is added to the worst load case (number 6). Las column of the table (“Comments”) states if the load case is actually calculated (“done”) or is bounded by a more conservative load case.

Local analysis on more stressed components are performed separately. Reactions (namely bellow reactions) are also analyzed.

Pressure load

Figure 5 shows a sketch for pressure load worst case (design pressure).

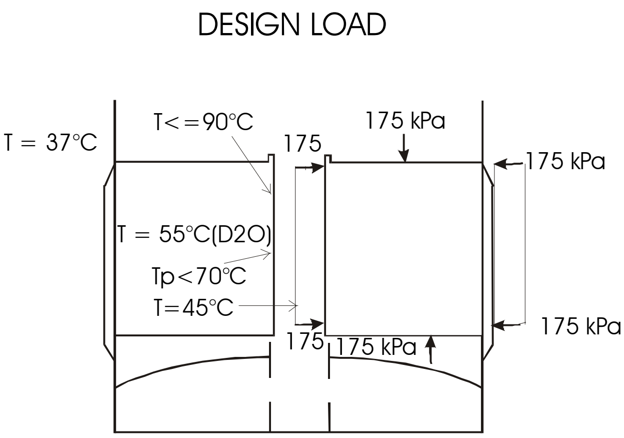


Figure 5 – Sketch for Design pressure load

Thermal loads:

A simplified conservative thermal gradient was applied. The maximum temperature difference between chimney walls (hottest zone) and vessel envelope is 33°C. Maximum temperature difference for Second Shutdown System (SSS) action is 50°C.

Zircaloy growth:

Neutronic flux induces Zircaloy growth in a given direction. The growth obeys a law defined by a curve. This effect was introduced in the model by means of a thermal analogy. The most significantly affected components are the chimney and nearest irradiation positions.

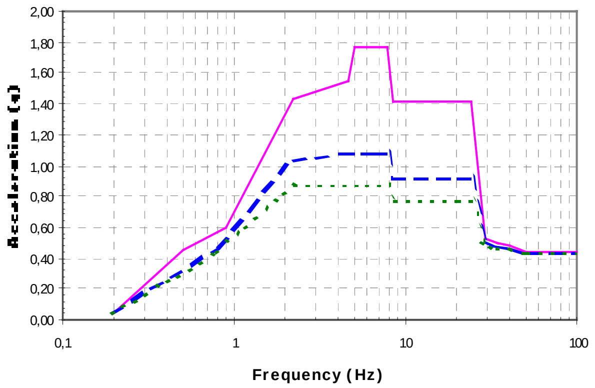
The flux varies with height along the chimney. The differences of flux pattern between the four chimney walls are small, so a symmetric arrangement was used.

To analyze growth, the chimney height was divided in 10 zones, computing the maximum flux in each one and a use rate of 90 % during a lifetime of 40 years.

Seismic Event:

The seismic spectra corresponding to severe earthquake for reactor pool floor level was employed (the RVE is fixed to this floor through other structures: plenum, suction box, core support structure). The equivalent static acceleration method was applied.

Figure 6 shows the maximum of the applied spectra.



Severe Earthquake – Level +0 m
North-South direction (X)
Reactor Block

Design Response Spectrum 2% critical damping
Design Response Spectrum 5% critical damping
Design Response Spectrum 7% critical damping

Figure 6 – Applicable severe earthquake – Floor level response spectra

3. FINITE ELEMENT MODELS

3.1 Global RVE model

The reflector vessel is not an isolated component. For this, along with modeling the pressure vessel and chimney, it was necessary to model the plenum, the suction box and the upper skirt along with some reinforcements as well in order to capture the behavior of the structure as a whole.

A finite element model was built using NASTRAN for Windows(ii) code. A four-node quadrilateral plate element was used for modeling the Zircaloy reflector tank and chimney, the Stainless Steel suction box and plenum and the upper Aluminum skirt. A two-node beam element was used for the Zircaloy irradiation position, and eight elements for columns. The model has a total of 8687 nodes and 8247 elements.

Figure 7 shows a section view of the global model labeled as follows:

a) Cylindrical wall of reflector vessel
b) Top and bottom heads of reflector vessel
c) Chimney (middle part)
d) Cold and hot sources wall
e) Cylindrical wall of Zircaloy suction box
f) Curve plate in suction box
g) Cylindrical wall of Stainless Steel plenum
h) Cylindrical wall of upper skirt
i) Core supporting structure flange
j) Cylindrical wall of Core supporting structure

k) Cooling system inlet
l) Heavy water suction
m) Heavy water outlet

Bellows in beam heads were modeled using translational spring elements in order to evaluate its influence in global structural behavior. No significant difference in modal frequencies was noted by including the bellows stiffness. The loads applied to the top of the chimney by the bellows and by the pipe are regarded as negligible.

Cold Beams and Cold Neutron Source ends are guided by mean of a structure linked to vessel bottom head. This structure is taken into account in the global model using beam elements and appropriate nodes degree-of-freedom links.

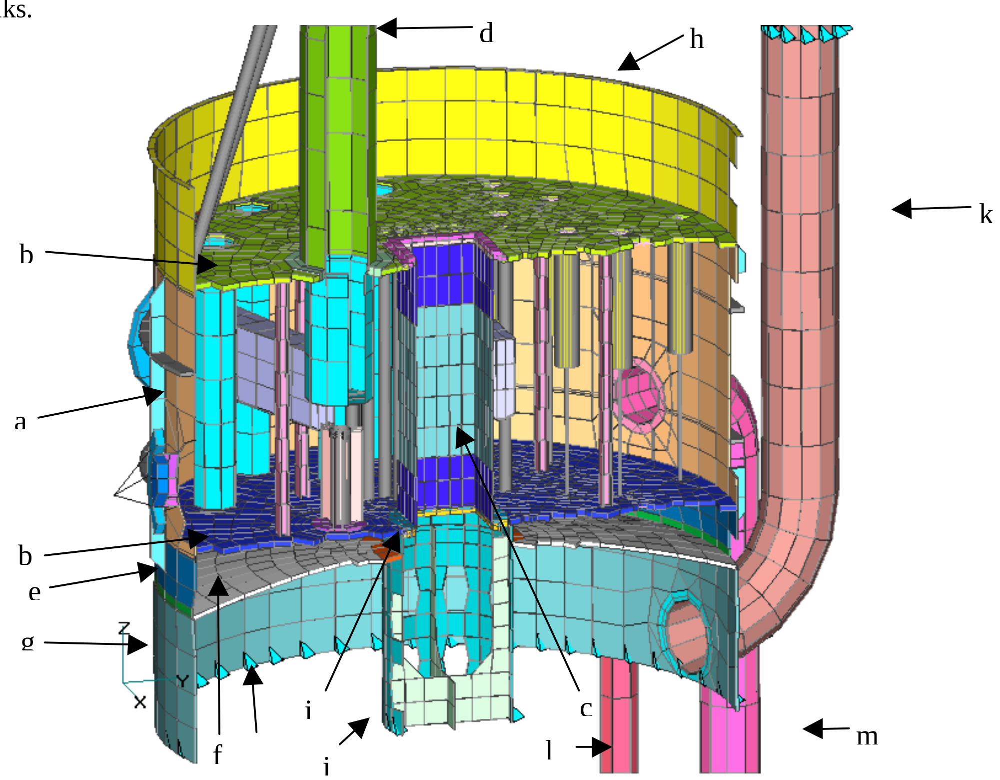


Figure 7 – Global model section view

Model constraints:

The model is analyzed with the following constraints:

a) The lower perimeter of the plenum (at pool floor level) is supported, i.e. the three translation degrees of freedom at each node are restricted.

b) The perimeter of the bottom of the chimney base is restricted to translate in the z direction linked to core support. A horizontal constraint links core support with plenum inner rig when appropriate.

Model mass:

Non-structural water mass, comprising internal and external associated water related to plenum, reflector vessel, neutron sources and upper skirt (for dynamic analysis) was added to the structural mass. Model total mass is 36600 kg.

3.2 Chimney model

The chimney was analyzed by means of a refined mesh model in order to capture the details of the behavior of different load conditions and designs details, such as different Zircaloy laminate directions.

Model Description

The chimney walls are thinner in the central (reinforced) part and thicker at corners and top and bottom ends. Figure 8 shows a global and a section view of the model.

Boundary conditions:

The chimney was fixed (three translational degrees of freedom) in its bottom end in all the analyses (all load cases).

Modal analysis (carried out in order to evaluate possible dynamic coupling between reflector vessel and chimney, during seismic event) was performed without any constraint in chimney upper flange. The objective was to obtain minimum frequency estimation with chimney upper end free, neglecting reflector vessel constraint.

For static analysis purposes, in order to reproduce the relative constraints and forces between both components, the refined model was loaded with the displacements obtained at the top and bottom of the simplified chimney in the whole model. Pressure, temperature and Zircaloy growth loads were applied under these conditions.

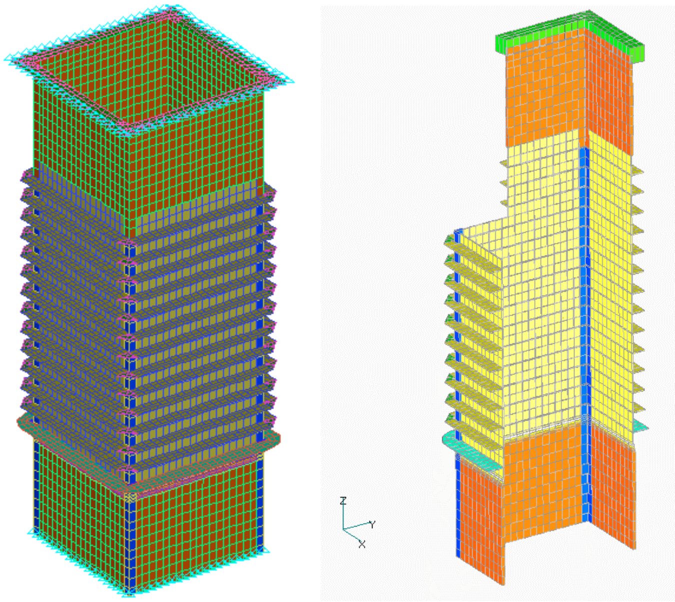


Figure 8 – Global and section view of chimney model

Vertical displacements due to pressure, temperature and Zircaloy growth loads take values not exceeding 0.5 mm.

Model mass

Model total structural mass is 115 kg. Non-structural mass includes the internal water and external associated water for dynamic analysis.

The model is composed mainly of four node plate elements.

4. GLOBAL MODEL: RVE ANALYSIS

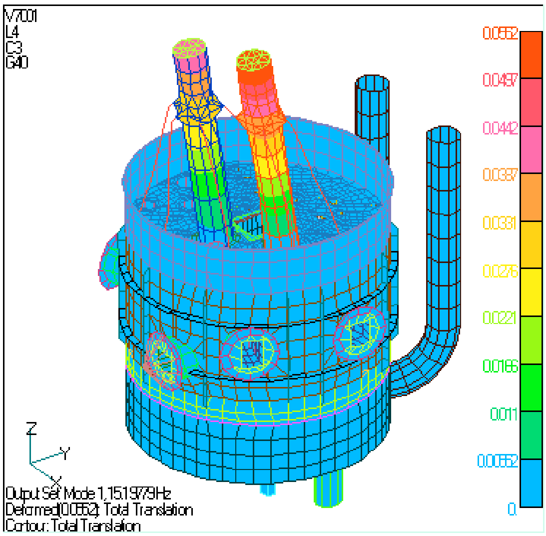
4.1 Modal analysis

Modal results are employed to evaluate seismic dynamic amplifications. First mode (Figure 9) is a cold and hot neutron source local mode (Y-direction), with a frequency of 15.2 Hz. First mode with some global mass participation is shown in Figure 10, with a frequency of 27.6 Hz.

4.2 Strength analysis

Results for three combined load cases are presented. Deformed shape and maximum stresses for normal operation load case and worst load case (design load plus seismic event) are shown in Figure 11 and Figure 12.

Maximum vertical displacements at RVE heads do not exceed a few millimeters. Maximum stresses during normal operation (combination of individual load cases a-i, b-i, c and e) are lower than half the allowable stresses. Worst case corresponds to combination of design loads and seismic event (combination of individual load cases a-ii, b-ii, c, d and e), and stresses are below allowable values. Maximum stresses on RVE wall are much lower. Maximum horizontal displacements on RVE top head do not exceed a few millimeters.



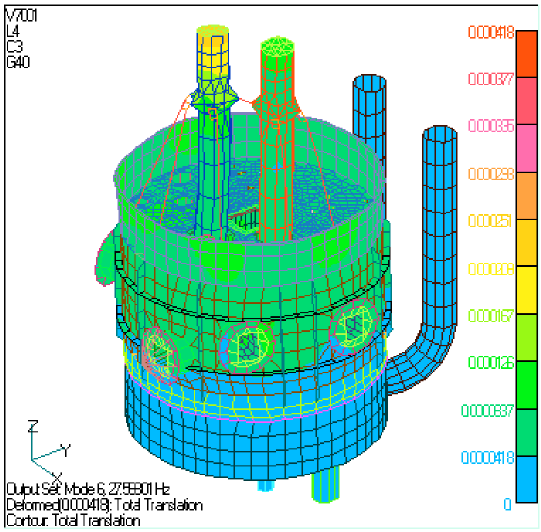


Figure 9 – First mode (local: cold and hot sources) **Figure 10 – First mode with some global participation (contour levels only for illustration)**

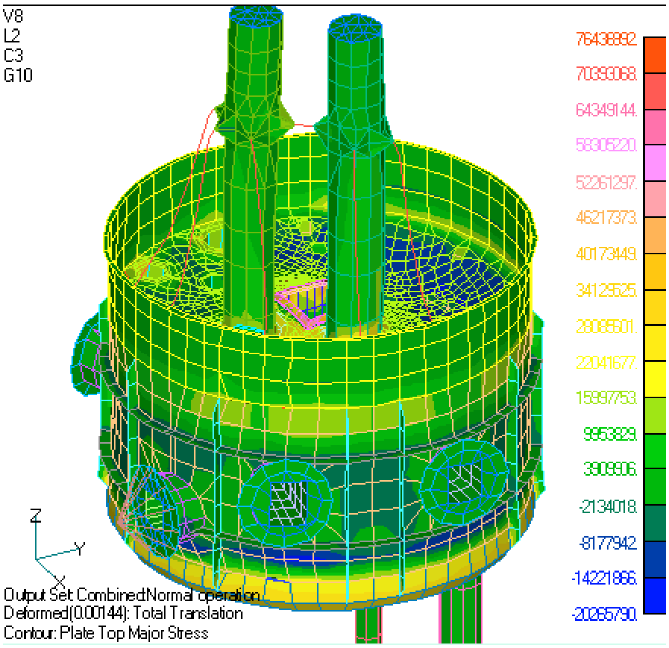


Figure 11 - Reflector Vessel: Principal Stress due to Normal Operation Pressure – Contour levels in [Pa]

4.3 Buckling

An analysis was performed on buckling of the reflector vessel under the major solicitation of the design load condition (design pressure case). A hinge connection between column and vessel heads was conservatively assumed.

The first buckling mode corresponds to local buckling failure of a column between vessel flat plates with a factor approximately 3.5 times the applied load. This gives a buckling pressure load on Reflector Vessel of 600 kPa. The deformation of the flat head is shown in Figure 13.

Shell first buckling mode is higher. The deformation of the cylindrical vessel wall is shown in Figure 14.

Regarding buckling of the pass-through columns, a buckling by-hand analysis was performed using the compressive load supported by each of the fifteen pass-through irradiation positions, columns and silicons according to numerical model results. From that analysis no pass-through column buckles, confirming model buckling analysis results.

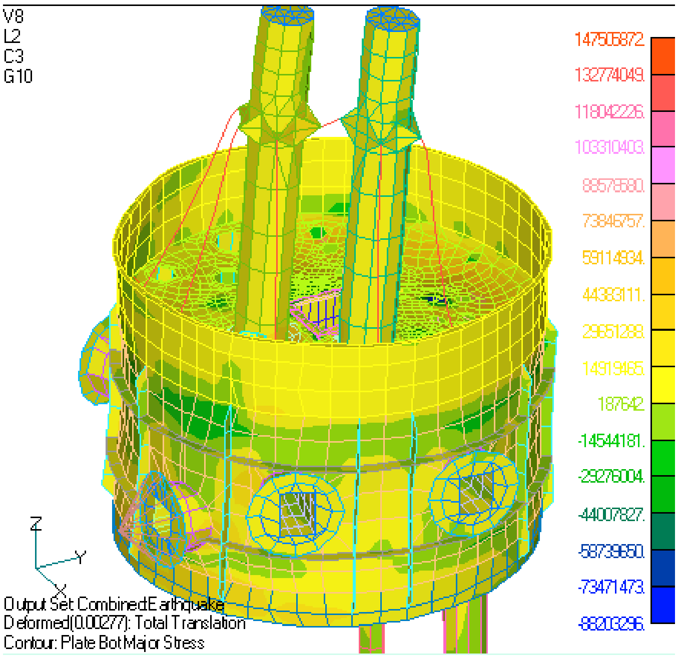


Figure 12 - Principal Stress under design and seismic event combined loads – Contour levels in [Pa]

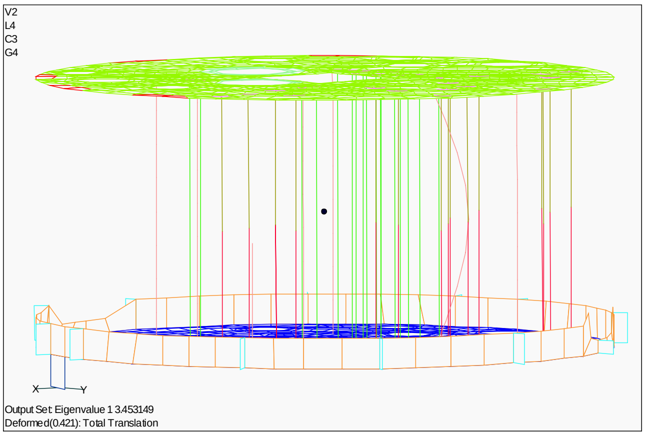


Figure 13 – Shape of first buckling mode (column)

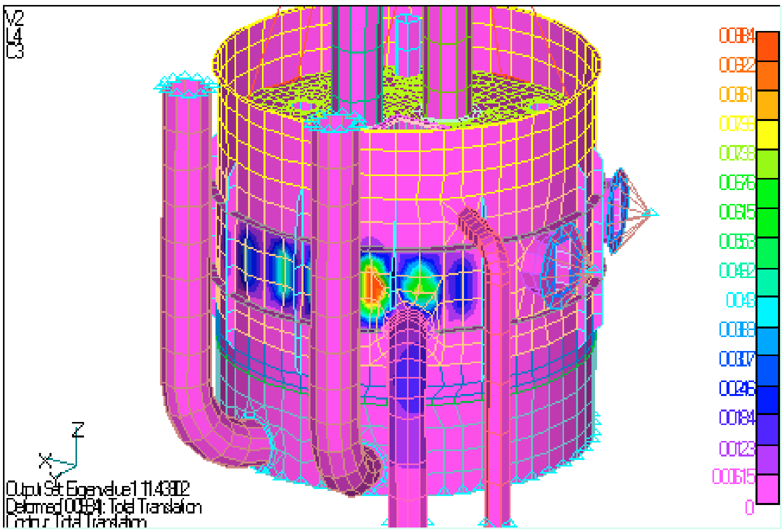


Figure 14 – Shape of first RVE wall buckling mode (contour values only for illustration)

4.4 Local analysis: beam connection

A local detailed analysis of union between beams heads and reflector vessel wall is carried out. The finite element model is refined around the connection, in order to obtain more accurate values –namely for maximum stresses.

A dynamic (modal) analysis was carried out to evaluate possible dynamic amplifications, obtaining a first mode at 33 Hz.

A static analysis was carried out, including design load pressure, temperature, Zircaloy growth, seismic event, bellow-induced forces (taken as an external load for the beam model). The influence of the guiding structure at neutron beam heads was also taken into account.

The results are shown in Figure 15. Displacements and stresses are well within allowable values.

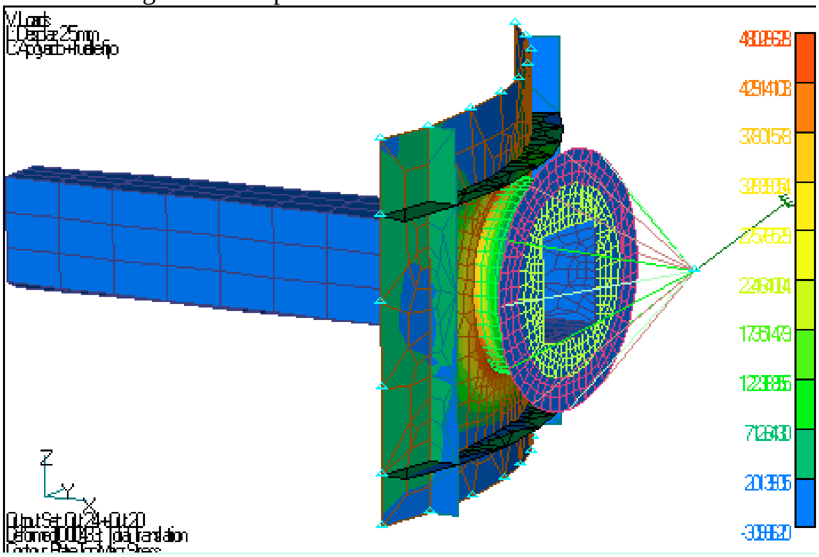


Figure 15 – Displacements and stresses under seismic event and maximum bellow displacement

5. CHIMNEY MODEL

5.1 Modal analysis

A modal analysis was performed under the boundary conditions already described, and a conservative first mode at 59 Hz was obtained. Modal results show a first mode uncoupled with global reflector vessel modes, well above rigid cut-frequency (40 Hz) and above any spectrum amplification frequency.

5.2 Strength analysis

Results for combined action of design pressure load, temperature, Zircaloy growth and own weight are shown in Figure 16. Maximum displacements at chimney wall are around 1 mm. Maximum stresses are within allowable values.

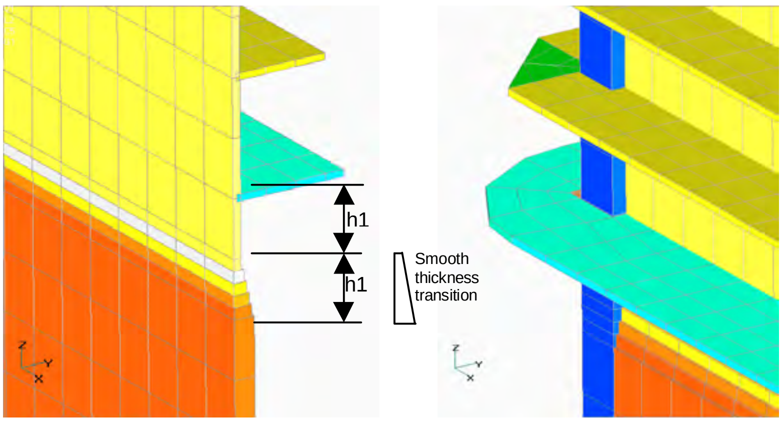


Figure 16 – Detail around maximum stress zone – wall thickness transition zone near corner – Length mm

A local analysis was carried out around the bottom reinforcement zone (wall thickness transition zone), under worst case loads. Analyzed geometry is shown in Figure 16.

Displacements induced on chimney top end by RVE head under seismic loads, obtained from global model under conservative hypotheses, were applied. Results show low stresses, with non-significant values over most of the structure.

Design was optimized taken into account worst case loads, including pressure gradient during a transient – SSS and primary system action during startup (Figure 17).

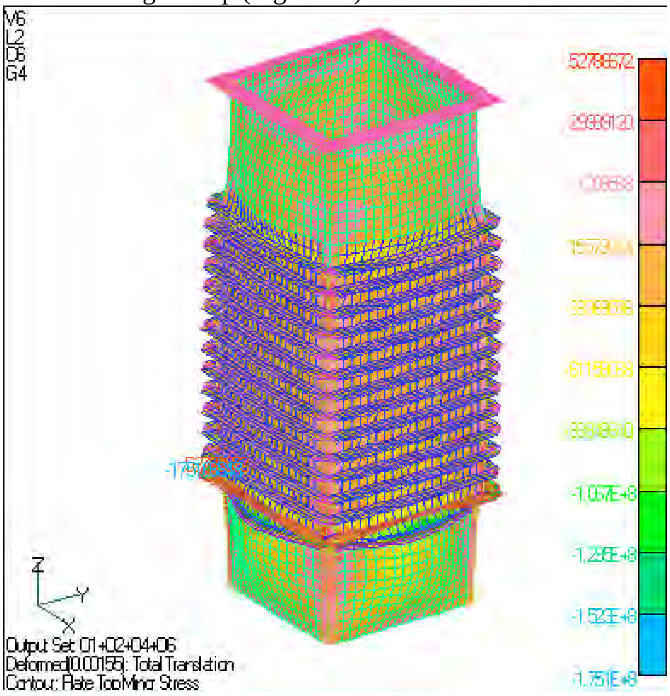


Figure 17 – Displacements and stresses under total combined load – Minimum principal stress (top face)

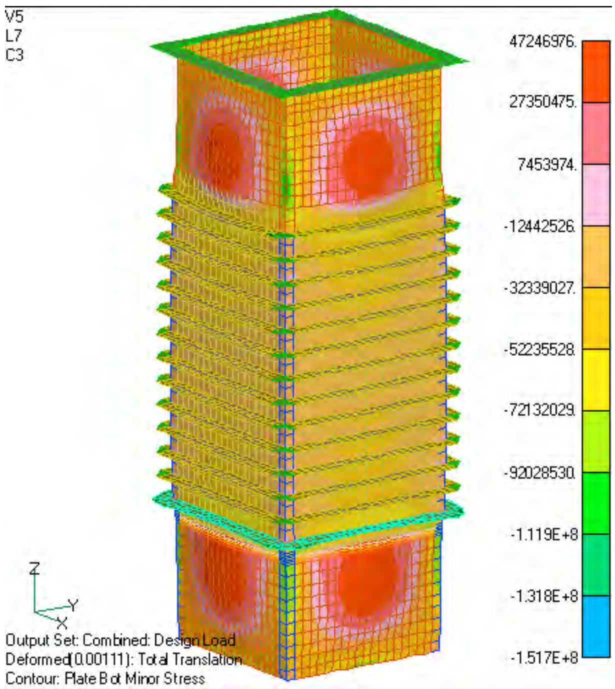


Figure 18 - Chimney displacements & stresses under design pressure, temperature and Zry growth [Pa]

The analysis includes conservative hypotheses such as simultaneous action of SSS and primary cooling system during startup (worst operating case), end-of-life Zircaloy growth and severe earthquake, in spite of which Service Level B were applied.

6. ACCIDENTAL/INCIDENTAL LOADS

Accidental/incidental loads were also verified, although as separate calculations. Here we mention succinctly the CNS explosion and the fall of an object over the reflector vessel.

A brief graphic illustration of impact test and CNS explosion analysis is shown in Figure 19.

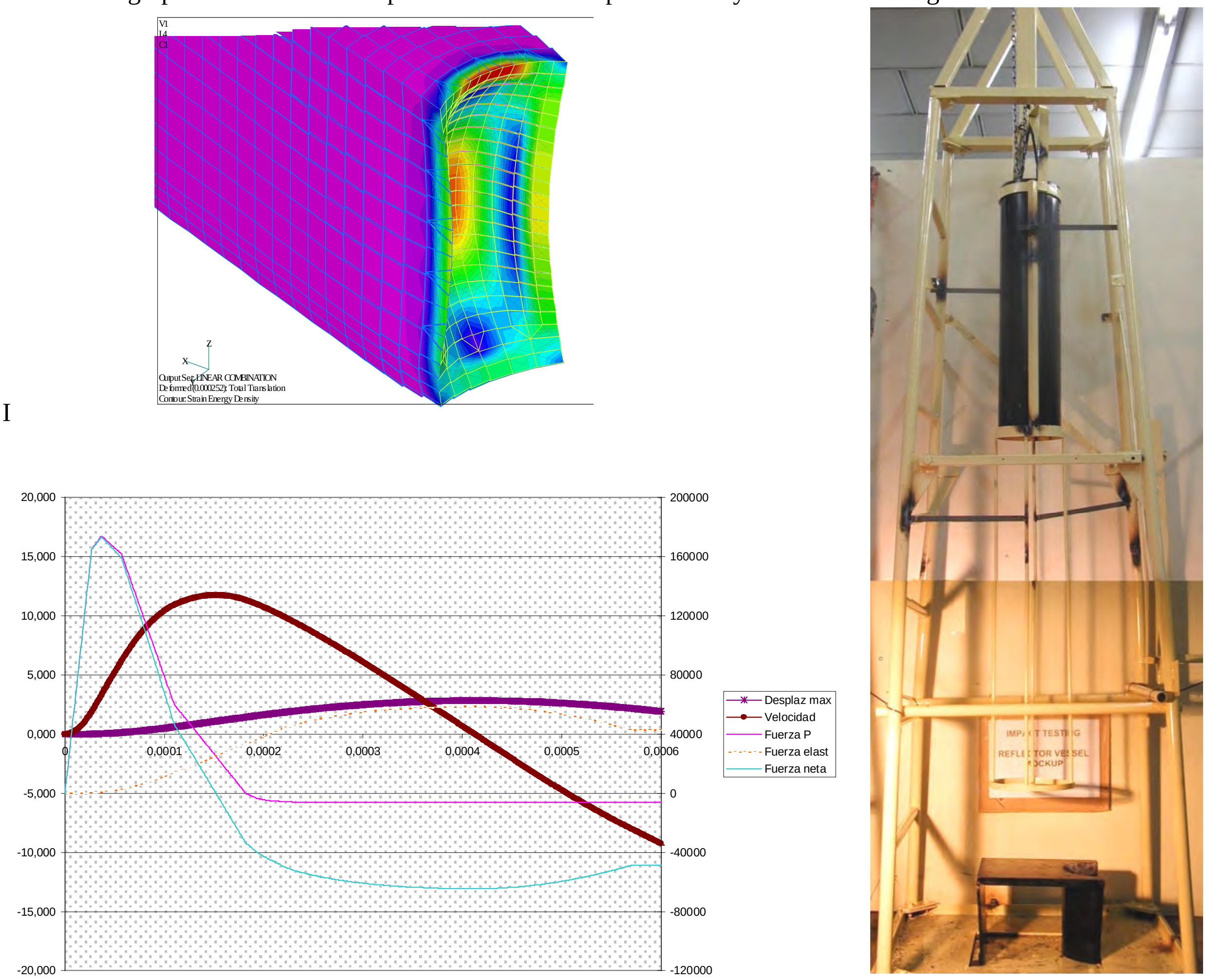


Figure 19 – CNS explosion analysis (left) – Impact test on RVE partial mock-up (right)

7. CONSTRUCTION DETAILS

The RVE was manufactured by means of precision welding and machining, in agreement with requirements by ASME III ND.

Welding on pressure envelope and accessories are butt-welding and fillet welding.

Pressure envelope, lifting points and lower cover were welded, but irradiation facilities and chimney were machined, then welded, and finally underwent a total machining.

Inspections are consistent with code requirements.

Manufacturing sequence was:

a) Forming of pressure envelope sheet.
b) Forming of top and bottom vessel heads.
c) Machining and welding of Neutron Beams flanges, Cold and Hot Neutron Sources, Chimney.
d) Welding of all pieces previous to pressure envelope.
e) Location of irradiation facilities for Rigs, Pneumatics, Neutron Beams, Cold and Hot Neutron Sources.
f) Welding of these facilities.
g) Final machining of facilities and contact surfaces (flanges, etc.)

Pertinent NTD and dimensional controls were performed during each manufacturing stage.

Simultaneously with this, the 5 Neutron Beams were built, under appropriate inspection and controls. After finalizing RVE manufacturing, the Beams were assembled with it as a single piece.

8. TESTS

Pressure Tests

The described analyses were partially verified by hydraulic tests –required by standards- of chimney and vessel.

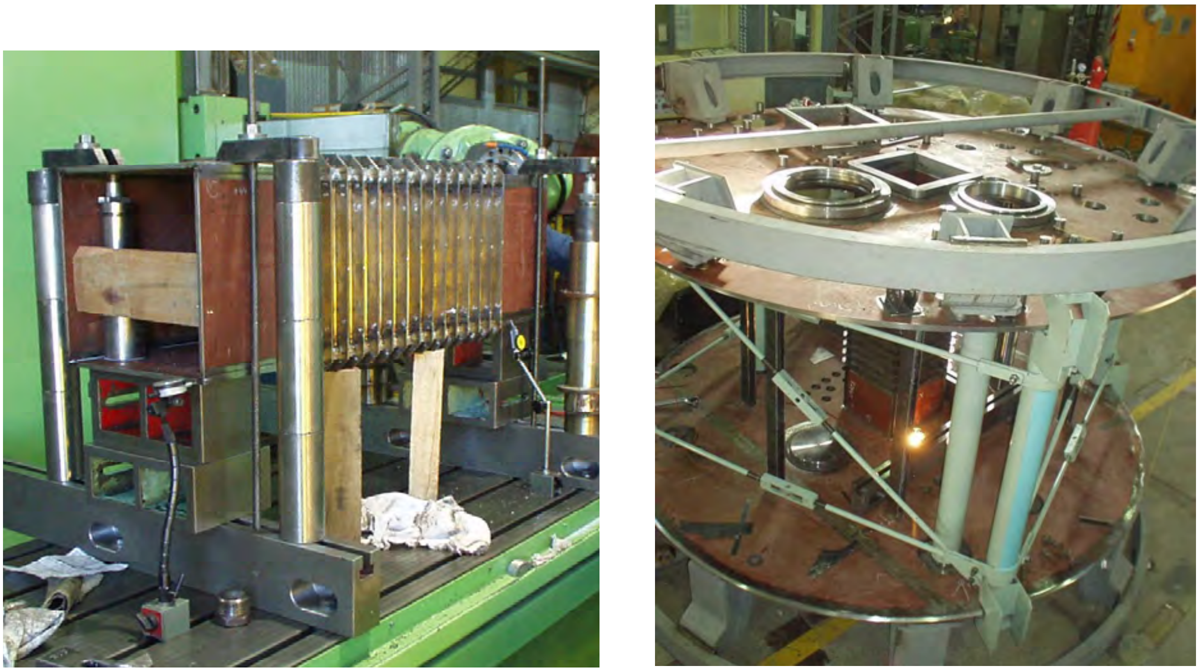


Figure 20 – Mock-ups of chimney and RVE made of steel

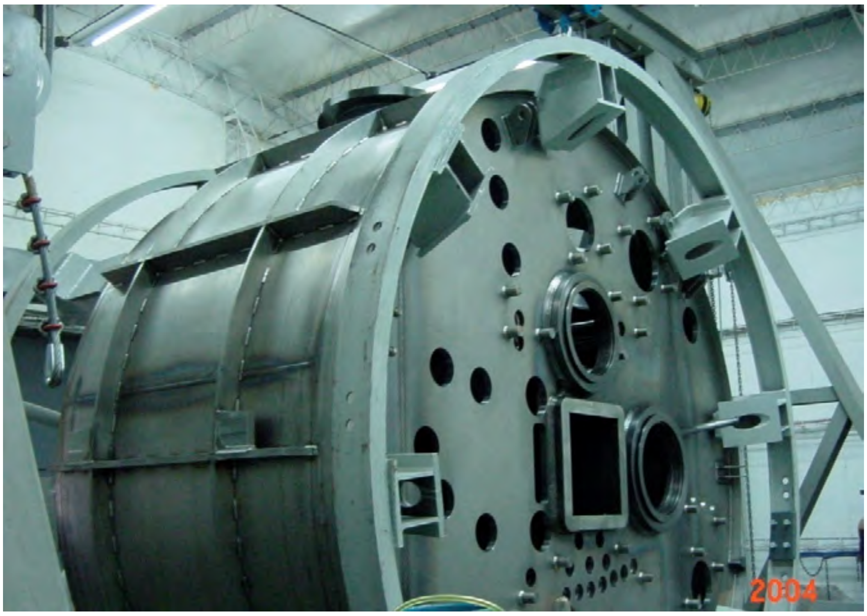


Figure 21 – Manufacturing of RVE of Zircaloy inside clean room

Design soundness regarding involved quantity, attributes and quality of welding and joints was initially verified by manufacturing of mock-ups. These mock-ups were geometrically identical to the final components, but made of different material (see Figure 20). Later the design was verified by standardized procedures on final components (made of Zircaloy; Figure 21 and Figure 22).

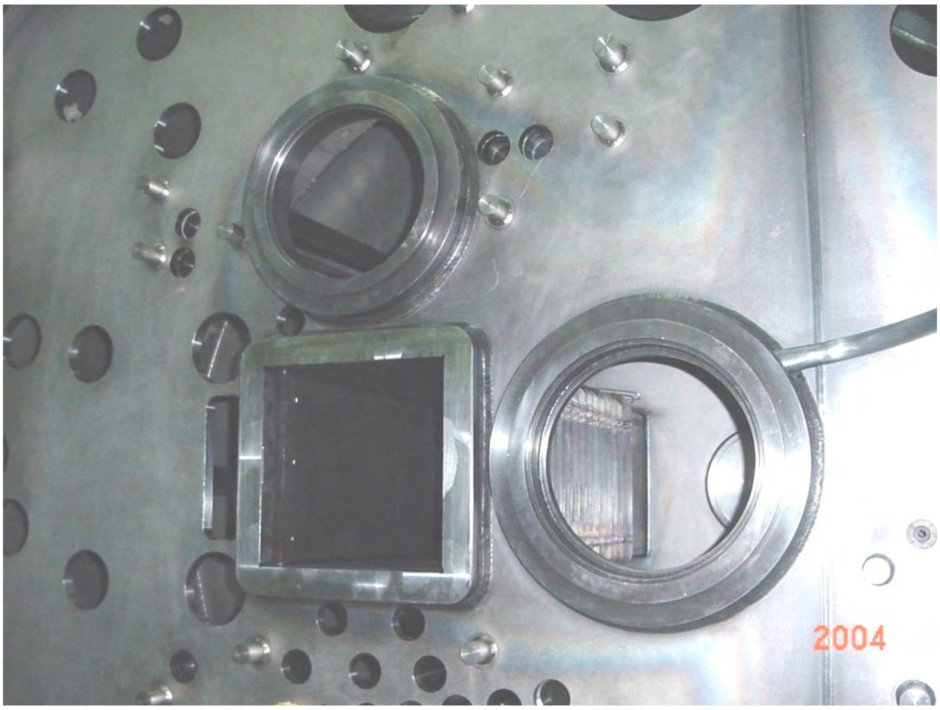


Figure 22 – Fabrication of RVE of Zircaloy

8. CONCLUSIONS

A global model and several detailed partial models were developed. 7 individual load cases were analyzed, combined in two main final load cases: normal operation and design loads simultaneous with seismic event. Preliminary analyses and iterative interaction with neutronic, thermohydraulics, materials and assembly sectors were employed to harmonize requirements and optimize design features.

Results from global and local analyses, under conservative hypotheses, show significant margins in normal operation, and displacements and stresses within allowable values in worst load case, for RVE components.

Buckling safety factors are generally high, and they are above minimum allowable values required by standards for all components.

Strength and acceptability of design and manufacturing were verified under pressure worst cases, by means of tests carried out on mock-ups and final components.

9. REFERENCES

[i] Normas ASME Boiler & Pressure Vessel / Code Section III, Subsection ND

[ii] MSC/NASTRAN for Windows – User Manual