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Advance Analysis of Gasket Pressure Vessel Closure System

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1. ABSTRACT

The pressure vessels have closure systems allowing visiting the inner of the component or used for maintenance activities during its operation. For these closure systems, in particular for nuclear components, their mechanical resistance and their leak tightness must be demonstrated.

The aim of the work was to develop a method to model completely a closure system, including the studs, the gaskets, the nuts, the flanges or covers and the part of the pressure vessel, for a 3-dimensionnal non-linear analysis taking into account the contacts between the gaskets and their seating surfaces as well as the non-linearity of the gaskets and the tightening preload of the studs. Therefore, with such a complete representative non-linear 3D model we can: (a) perform the stress analysis in all elements of the systems for all the operating conditions (thermo-mechanical transients) of the component and demonstrate their mechanical resistance (stress limit, fatigue, fracture, etc.) and, (b) analyse the behaviour of the contacts between the gasket and its seating surfaces, for all the operating conditions and so, to estimate the history of the compressive forces on the gaskets and to demonstrate that the necessary conditions for the leak tightness are met, particularly the metal-to-metal contact for multi-ring (metallic-graphite-metallic) gaskets and as an important, the re-calculation of the necessary tightening preload applied to the studs by the tensioner. The method was used for the behaviour analysis of manholes, hand holes and eyeholes of nuclear components. The results are meeting the requirements of the nuclear regulations and standards such as RCC-M, ASME,... The method was successfully applied for hydraulic tests of actual nuclear components.

2. INTRODUCTION

The developed method is based on the analysis of the variation of the contact forces exerted on the elements making up the multi-ring gasket (metallic-graphite-metallic) in order to verify that the compression forces are maintained during all operating conditions of closures.

When forces continue to take the form of compression forces, at least on the graphite ring and on the outer steel ring, it can be assumed that the conditions necessary to ensure leak tightness are respected.

The analysis is performed using a given initial tightening value while taking into account the impact of the transients by means of non-linear resolutions of the model of the closure system which is doted with specific finite contact elements to simulate the component parts of the gasket.

Therefore the method consists of calculating the contact reactions which occur at the level of the various elements of the gasket in order to verify that at the most «pressure-released » instant, these reactions remain compression reactions and continue to ensure contact.

The method is divided into two phases:

- Search among all the operating situations, the situation showing the most « released » instants,
- Once the situation is identified, a non-linear thermo-elastic resolution of the model is performed to evaluate the reactions in the zones of contact.

The calculation is done using SYSTUS multi-physic software.

3. DESCRIPTION OF THE MODEL

Because of the geometrical symmetry (connection taps on the cylinder shell and distribution of the stud bolts) a quarter of the closure is represented in the three-dimensional model.

The mesh system is composed of second order elements with 138597 nodes and 35439 elements (Figure 1).

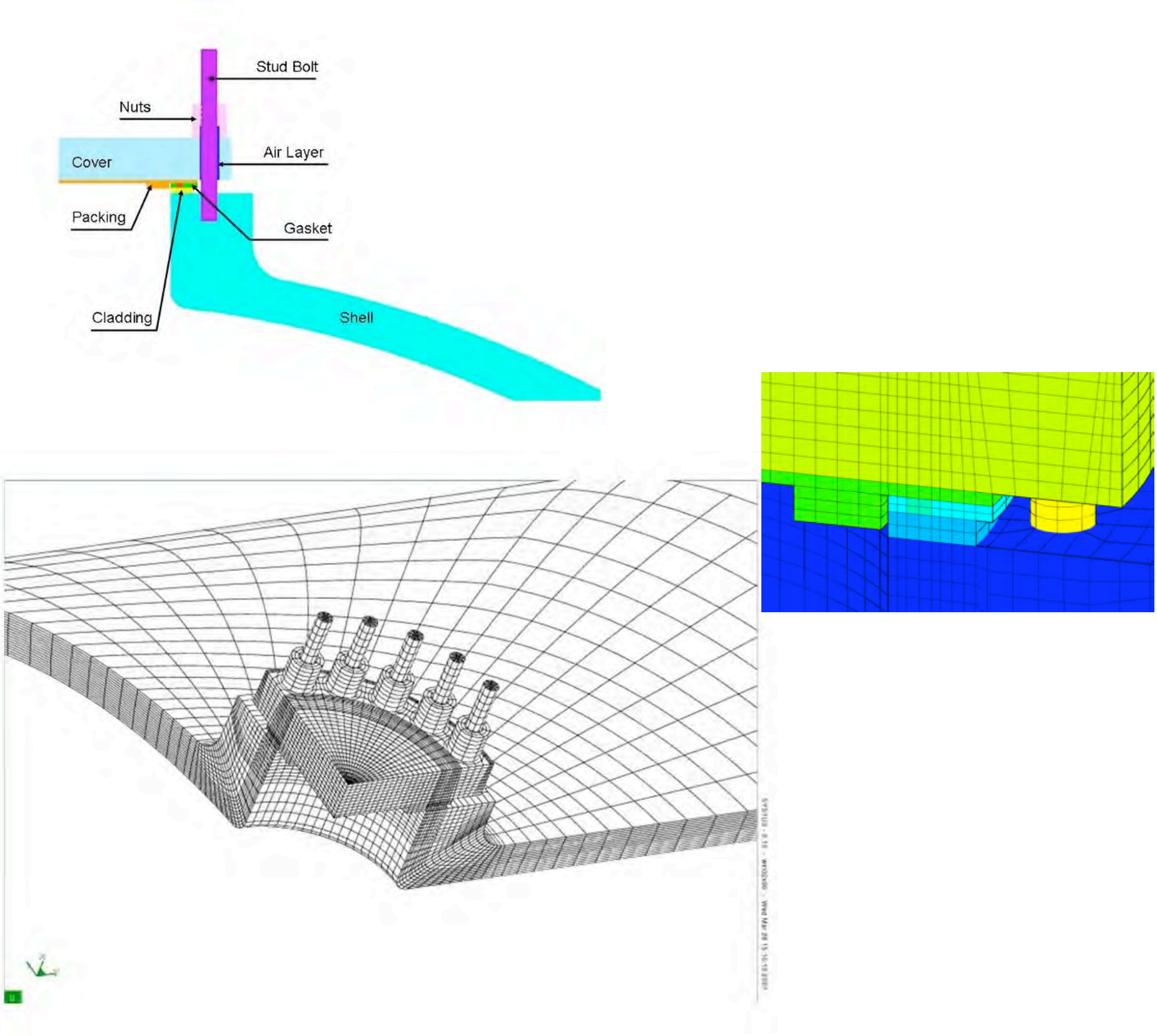


Figure 1. Mesh system and model

The stud bolts are modelled with a constant section: the measurement retained is the diameter at the base of the thread in the zones trapped between the pad and the nut. Threads of the stud bolt are not modelled. The geometry of the nuts is simplified.

The thicknesses of the structure to be taken into account are defined according the RCC-M codification.

3.1. Modelling of the contact zone

In order to evaluate the contact reactions, the contact between the gasket and its seating surfaces is analysed using specific finite elements known as «3D contact elements».

Contact is a geometric non-linear phenomenon. The contact model used is a Gauss point to Gauss point sliding surface model adapted to quadratic elements. The link between the gasket (inner steel ring + graphite ring + outer steel ring) and the cladding of the seating surface is realised using contact elements (bearing contact and target Gauss points). By integrating these contact elements, it is possible to calculate the resulting load on each contact zone.

The calculation is performed using a non-linear three-dimensional model simultaneously taking into account the initial tightening, the internal pressure and the thermo-mechanical loads.

The graphite part of the gasket is modelled according to measurements obtained from a graphite compression/release test. In Figure 2, the curve indicates the quantity of matter crushed before reaching metal/metal contact and the force necessary to achieve it. In the gasket model, the graphite ring is represented with a greater thickness than that of the steel rings, taking into account by this way the first compressive phase of the graphite.

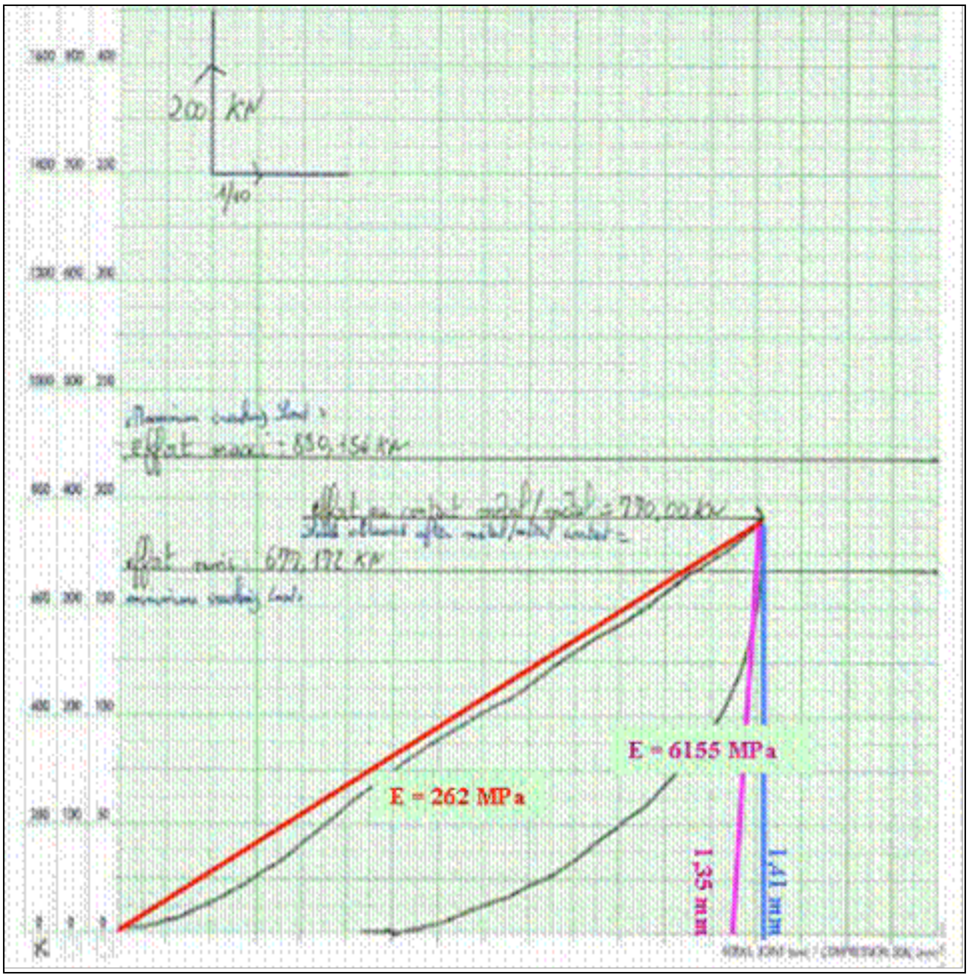


Figure 2. Compression (load) / release (unload) curve for the graphite ring

The behaviour of the graphite ring is represented, first, by an initial deformation corresponding to the crushing leading to the metal/metal contact of the steel rings as described above, and secondly by a stiffness expressed in the Young modulus under the load compression phase and under the beginning of unload phase, quantified using the curve of the load/unload tests in Figure 2.

The initial tightening force is modelled by an initial deformation applied to the free part of the stud bolt barrel, as show Figure 3.

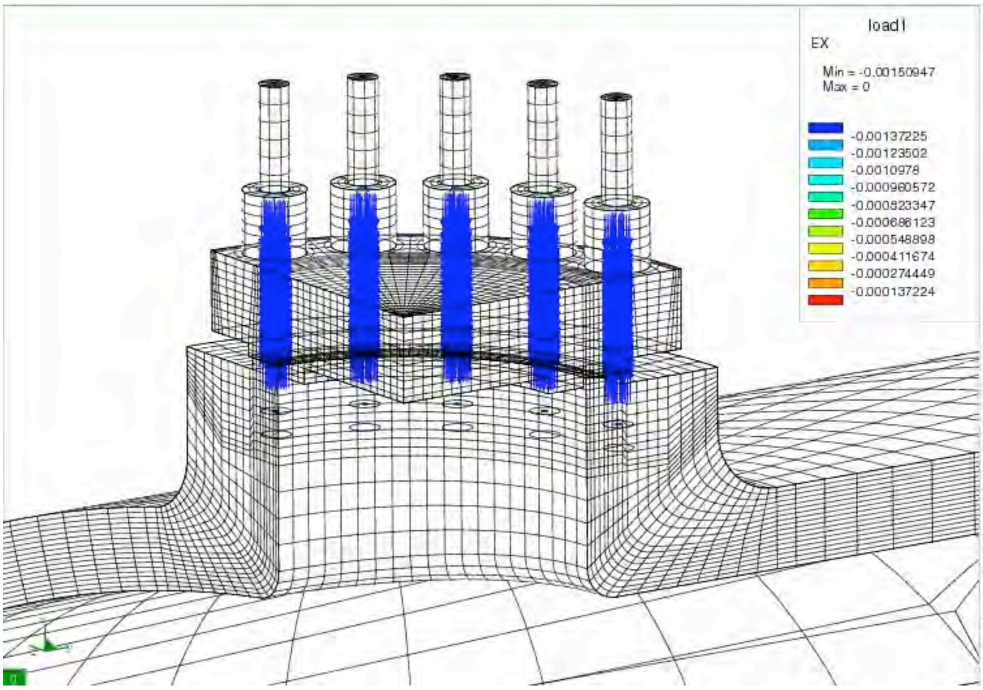


Figure 3. Pre-stress loads of the stud bolts

3.2. Definition of the initial tightening

According to the RCC-M, the maximum initial tightening force is defined at full rate test pressure and at 50°C (Formula (1)):

$$FS(Pe) = FF(Pe) + FM(Pe) \qquad (1)$$

- Pe is the test pressure taken at the theoretical test value
- Pressure load $$FF(Pe) = \frac{1}{4}\pi . D_j^2 . Pe \qquad (2)$$
- Sealing gasket tightening force required to ensure leak tightness under test condition pressure:

$$FM(Pe) = m.Pe \cdot \pi \cdot \left(\frac{De^2 - Di^2}{4} \right) \qquad (3)$$

  - Dj : Average diameter of sealing gasket
  - De : External diameter of graphite
  - Di : Internal diameter of graphite
  - m : Holding ratio

4. MATERIALS

The materials of the constituent parts of the inspection hole are listed below:

- Shell and cover: 18MND5,
- Stud bolt: 42 CDV4,
- Nut: 42CrMo4,
- Cladding: Inconel 690,
- Packing ring: Z2 CND 17.12,
- Sealing gasket: Graphite core and Z2 CND 17.12.

The properties of the graphite are provided by the gasket constructor.

We assume that the sealing gasket only works in compression during the initial tightening and in decompression during operating situations.

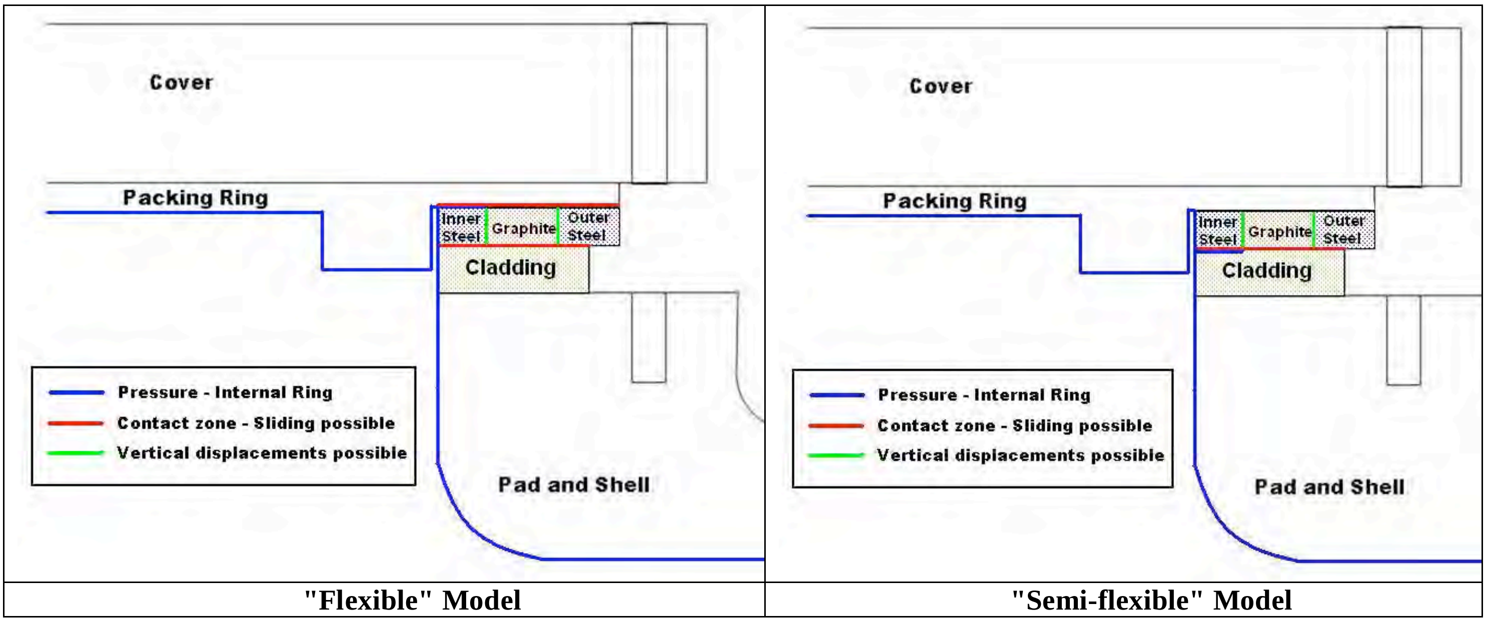
5. SENSITIVE ANALYSIS OF THE CONTACT AREA

The aim of this analysis is to show how the contact forces can be determined using different hypotheses and models in order to obtain the best possible view of the behaviour.

The sensitive analysis concerns the two following situations:

Case 1: The gasket is modelled in the assembly with contact elements disposed on the upper and lower surfaces and with a degree of freedom (sliding at the interfaces of the rings), the model is qualified as « flexible ». The retained tightening value at full rate pressure corresponds to the first deformation by the crushing of the graphite ring.

Case 2: The gasket is modelled in the assembly with a permanent contact on the surface in contact with the packing ring and with contact elements disposed on the seating surface; the model is qualified as « semi-flexible ». The same tightening condition is used as above.



"Flexible" Model **"Semi-flexible" Model**

Figure 4. Flexible and Semi-flexible models

The material properties are taken at 50°C.

Tables 1 and 2 below list the values of the compression forces obtained for the initial tightening alone and under operating pressure throughout the complete gasket.

Table 1. Initial state – Tightening only

Model	Compression force in the gasket's component FX (N)				Theoretical tightening (N)
	Inner steel ring	Graphite ring	Outer steel ring	Total	
Flexible	3588	898400	1605528	2507516	2533340
Semi flexible	0	1002872	1552020	2554892	

Table 2. Operating condition – Tightening and pressure.

Model	Compression force in the gasket's component FX (N)			
	Inner steel ring	Graphite ring	Outer steel ring	Total
Flexible	0	855772	35200	890972
Semi Flexible	0	926568	27168	953736

From these results, we note that the contact at the level of the inner steel ring is barely established during the initial tightening due to the geometry and to the deformation of the component parts of the closure system under pressure. However, the graphite ring and the outer steel ring keep in contact.

Basing our choice on the reaction of the outer steel ring, the most conservative model is the « semi-flexible » model. Therefore, the leak tightness analyse is leading using this model.

6. BEHAVIOUR ANALYSIS

The behaviour analysis of the closure is composed of:

- Stress analysis based on a static linear analysis, the contact zone being fixed. Search among all the operating situations, the situation showing the most « released » situation for leak tightness analysis,
- Leak tightness analysis based on a non-linear thermo-elastic analysis on the previous identified situation.

6.1. Stress Analysis

The stress analysis for operating conditions is performed following RCC-M codification.

A simplified modelling of the contact area is considered: the graphite and the external ring are stuck to the structure. The internal ring is not stuck and pressure is applied between the internal ring and the cladding.

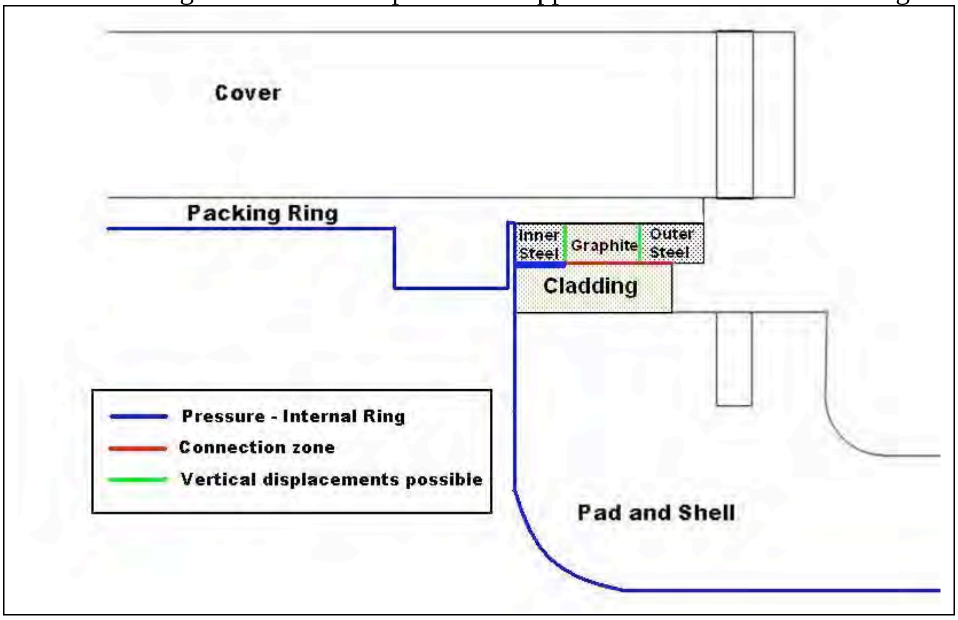


Figure 5. Semi-flexible model used for the stress analysis

6.1.1. *Loading*

The calculation is a static linear computation based on linear combinations of the initial tightening force, the internal pressure and temperature evolution of the operating conditions. Operating conditions are made up by about twenty transients. Figure 6 shows an example of one thermal/pressure transient.

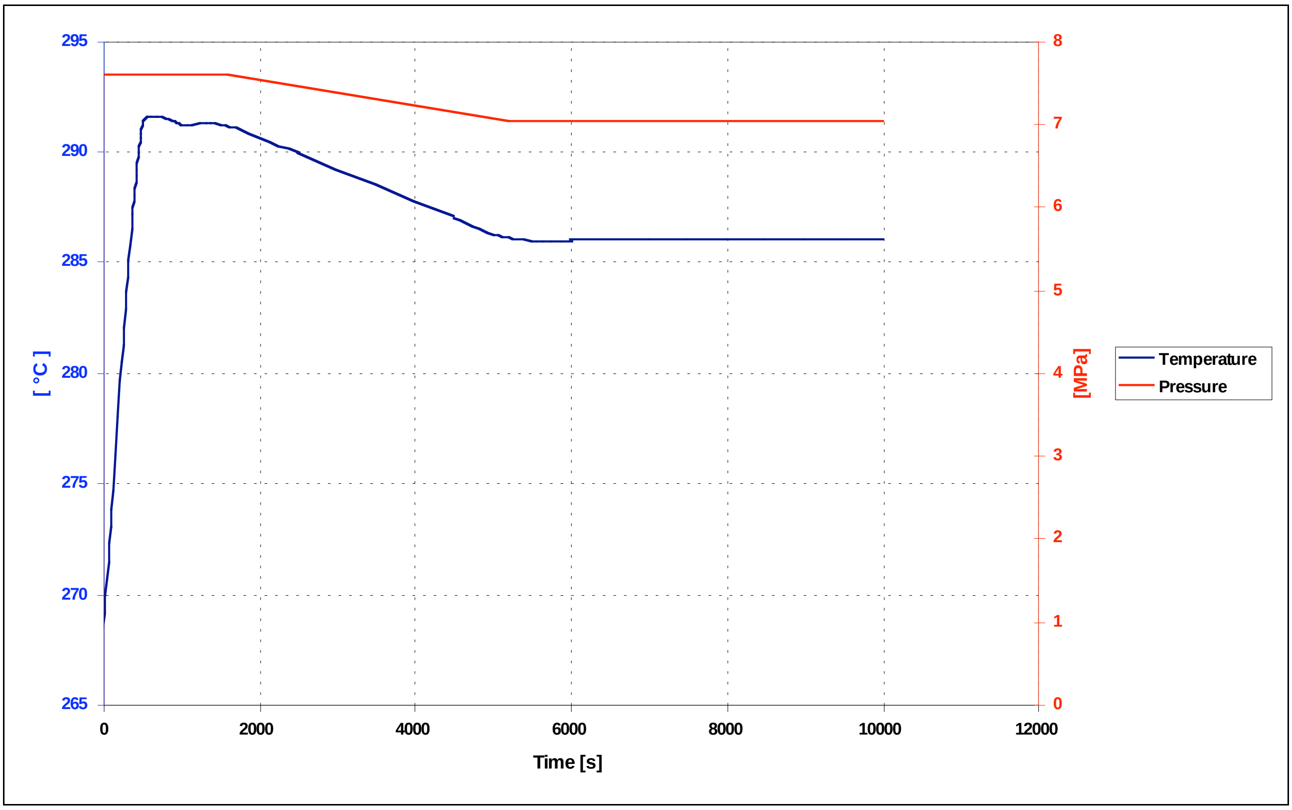


Figure 6. Example of fluid temperature and pressure variation of an operating condition

For the operating conditions loadings, thermal and thermo-elastic calculations are performed to evaluate the stresses created by the cumulative effects of the tightening of the stud bolts, the pressure and the temperature gradients.

The thermal loading is applied in the form of an imposed fluid temperature to the surface mesh elements through a heat exchange coefficient on the packing ring, gasket, cladding and shell.

On the outer wall, the exchange coefficient is null as we assume that the component is perfectly insulated.

The model extremities are assumed to be adiabatic.

In the gasket contact zone, the thermal contact is assumed to be perfect. The air layer enables to ensure continual heat exchange between the cover and the stud bolt.

6.1.2. *Stress Analysis and verification of the criteria*

According to the RCC-M chapter B3200, the stress analysis is performed on normal sections of the mean fibre. These sections are located in the zones of maximum Tresca equivalent stress, in the general zones and in the local zones, (connections, reinforcements, welds).

The criteria must be complied with RCC-M rules for the operating conditions.

The verification of level A criteria leads to three types of analyses: Analysis at 3 Sm, fatigue analysis with calculation of the usage factor and analysis of the thermal ratchet.

The purpose of the analysis at 3Sm combined with the analysis of the thermal ratchet is to secure the equipment against progressive deformation damages.

The purpose of the fatigue analysis is to secure the equipment against progressive cracking damages.

The RCCM procedure of SYSTUS is used to calculate the stress amplitudes in the sections in order to perform 3Sm, fatigue et thermal ratchet analysis and compare them to the criteria.

As an example, Tresca stress evolution (temperature only, without initial tightening and pressure) in the three more loaded nodes of the shell for a transient is shown figure 7 below.

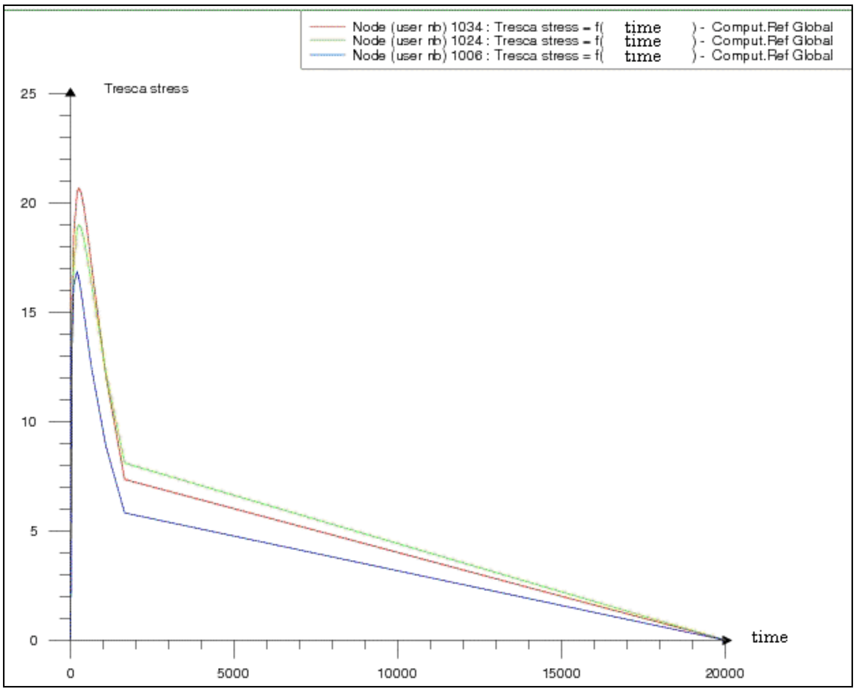


Figure 7. Thermal Tresca stress evolution for three nodes of the shell for a transient

6.2. Leak tightness under operating conditions:

6.2.1. *Selection of the thermal transients*

The transient presenting the most « released » instants, i.e. those with the minimum force on the gasket, is chosen among all the operating conditions situations computed for the analyses of operating conditions.

For each selected transient, the force passing through the gasket is plotted over time (Figure 8). The comparison of the plotted curves allows for determining the transient which presents the minimum compression force on the gasket.

Thus we retain this transient, named Critical Transient in term of potential leakage or loosing of leak tightness, to analyse leak tightness under the operating conditions.

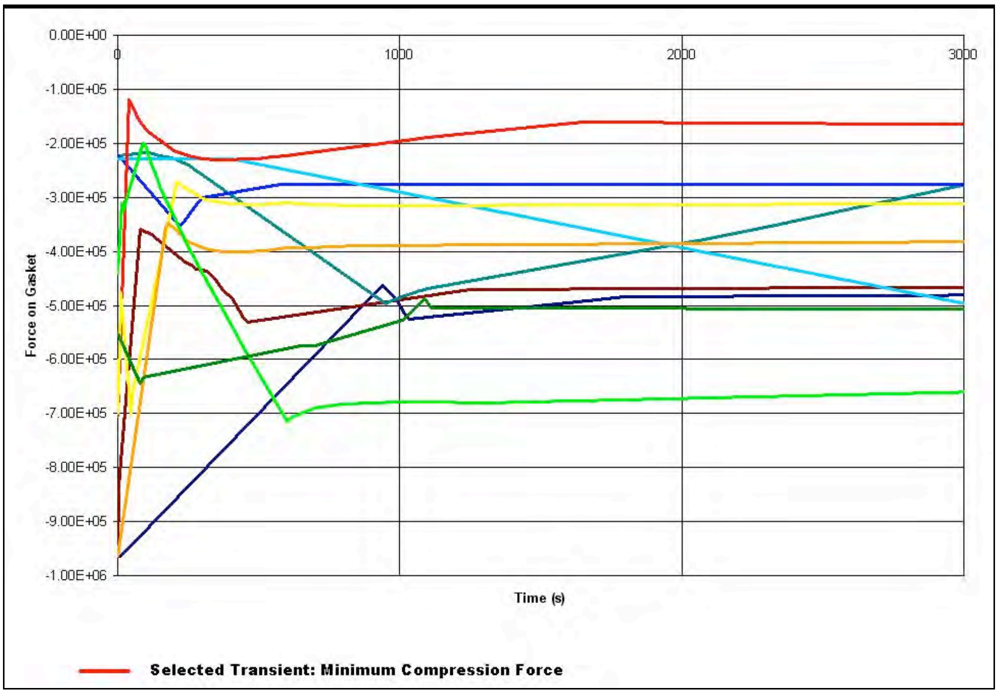


Figure 8. Evolution of the compression force between gasket and cladding for the selected transients

6.2.2. *Loading*

The pressure is applied on the inner surface of the structure at the level of the inner steel ring, the graphite as well as the outer steel ring is assumed to maintain contact. To the internal pressure is associated the end effect of the shell.

The non-linear calculation simultaneously takes into account the initial tightening force, the internal pressure, the temperatures within the structures at each calculated instant of the critical transient.

6.2.3. *Calculations and Results*

To judge the leak tightness, we analyse the reactions in the three ring of the gasket (inner ring, graphite ring and outer ring). If these reactions continue to be in compression, thus signifying that the contact is maintained, we will conclude that all the conditions necessary to ensure leak tightness are reunited.

In these conditions, the evaluation of the risk of loss of leak tightness consists in searching the minimum reaction in the graphite ring and inner/outer steel rings values attained for the critical transient that shows the weakest compression force on the gasket during the linear analysis.

Figure 9 illustrates the evolution of the force transiting between the gasket and the cladding according to the instants of the critical transient, respectively for the inner steel ring, the graphite ring and the outer steel ring. The totality of the Force passing between the gasket and the cladding is also included.

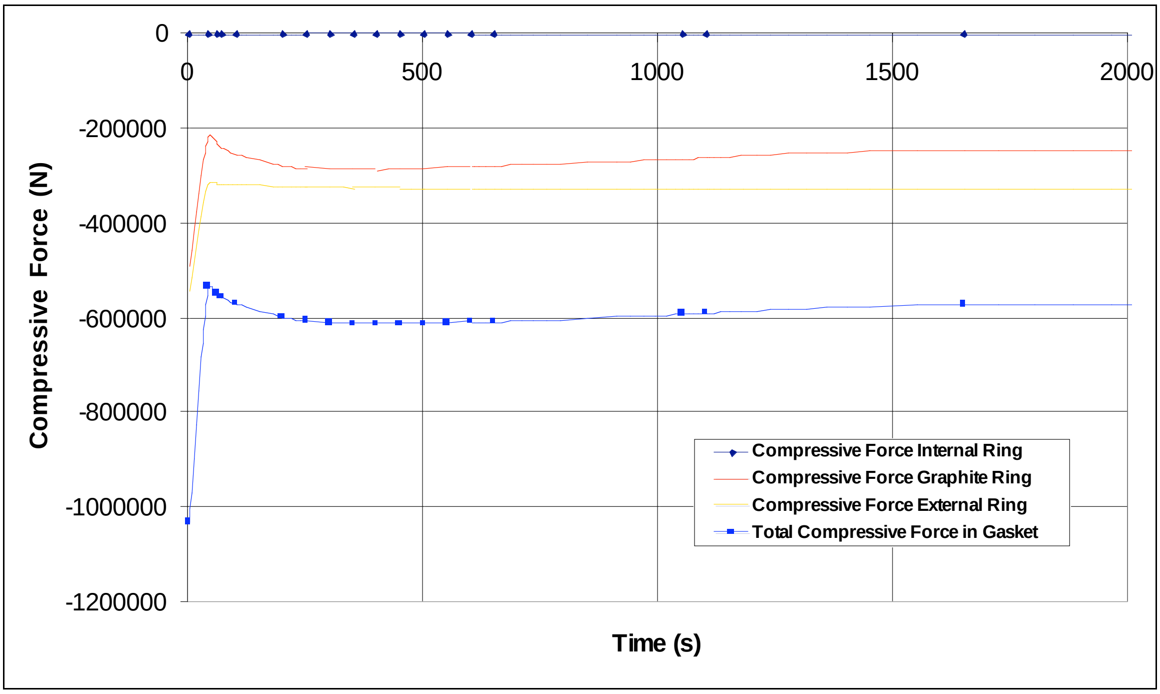


Figure 9. Evolution of the compression force between gasket and cladding for the selected transient

6.2.4. *Analysis of the leak tightness*

Table 3 synthesises the results of the leak tightness analysis at the least compressing instant of the critical transient.

Table 3. Minimum force transiting between gasket and cladding during the critical transient.

Compression force in the gasket's component: FX (N)			
Inner steel ring	**Graphite ring**	**Outer steel ring**	**Total load on gasket**
0	-216395	-317000	-533396

From the results above, we conclude that the values of the forces passing between the gasket and its contact zones change during the critical transient defined below as the most severe transient of the operating conditions in terms of potential leakage or loosing of leak tightness, remain compression forces at the level of the graphite ring and of the outer steel ring, showing, in particular, that the metal-metal contact is kept for the outer steel ring.

Thus, the minimum conditions necessary to ensure leak tightness are met for the critical transient and accordingly for all operating conditions and as a consequence, the determination method of the initial tightening load is validated.

7. CONCLUSION

The three dimensional modelling of the closure system of inspection holes and non-linear analysis included special contact elements allow predicting that the contact forces exerted on the elements making up the gasket continue to maintain compression during operating conditions of closures and in this way ensure leak tightness.

This method was applied to openings of nuclear components for the justification of leak tightness of the in-service operating conditions.

In particular, the method was applied for the calculation for the initial tightening load for the hydraulic test condition for which no leakage was observed. This test can be considered as a successful scale test.

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