

An original leak test for the Cirene Nuclear Plant

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1 INTRODUCTION

The methodology herein described has been applied to the Cirene Nuclear Plant, an Italian Heavy Water Moderated, Boiling Light Water Cooled, Natural Uranium Fuelled Reactor.

This Plant is equipped with a stainless steel Calandria named the Reactor Assembly having two functions:

- 1) to contain the moderator (Heavy Water) which fills it except at the top where slightly pressurized Helium is present
- 2) to support the Calandria Tubes containing inside the Pressure Tubes wherein the fuel is located.

The gap between the Biological Shield and the outside Calandria walls is filled with light water which shall cool the Reactor Assembly and furtherly shield the radiation.

During the fabrication all the weldments connecting the various portions of the Reactor Assembly, in compliance with the applicable Code (1) requirements, were tested by Helium. Once positioned in the Reactor Cavity and temporarily connected to the Containment Building, the Calandria Tubes have been joined to relevant appurtenances built in the upper and lower plates by means of a rolling technological procedure.

After that the definitive connection of the Reactor Assembly to the Containment Building has been carried out.

At this stage, before assembling the Pressure Tubes inside the relevant Calandria Tubes, the Hydrostatic Pressure Test of the Reactor Assembly in compliance with the ASME Code (1) requirements was planned.

The Hydrostatic Pressure Test had the scope: 1) to demonstrate the adequacy of the component; 2) to evaluate at certain characteristic locations the state of stress to be compared to the computed one; 3) to prove all the joints were tight.

Since an overall inspection of all the joints, as required by the ASME Code, and running a pneumatic test wasn't practicable a peculiar

procedure to estimate and compute a contingent leakage using a liquid medium has been conceived and tuned up.

2 COMPONENT PRESSURIZATION

The pressurization of the Reactor Assembly has been got using a very simple gear. It essentially consisted in a small diameter tube more than 10 meter long (a Piezometric Tube) filled with water up to the height corresponding to the test pressure (1.57 Ata at the level of the bottom of the Reactor Assembly).

The Piezometric Tube ended with a large diameter transparent container, whose aim was to check any changes of the level of the water free surface. The size of the container was set in order to avoid that a variation of the water free surface level could cause a significant variation of pressure.

The instrumentation chain was set up on the basis of the specified allowable leak rate (1.5 liter per day).

Two tests have been run. The first as part of a set of other tests, while the second one alone.

To reach the maximum pressure (the test pressure) it has been followed a path with intermediate steps of pressure (at fractions of the maximum pressure) in order to measure the state of stress during pressurizing up and down. The leak test has been performed at the maximum pressure over a period of 125 hours (of which only 84 hours useful for the measure) for the first test and of 72 hours for the second test.

The main difference between the first and the second test was the impossibility to use during the last one any internal temperature sensors.

The consequence of this difference was the necessity to use a correction factor to compute the leak rate associated to the second test. Anyhow the first test proved that the influence of that measure wasn't significant on the overall result, so that also the error introduced by using a correction factor was anticipated to be small.

3 THEORETICAL BASES

Since no analogous experiences were known to the Authors, it needed to build an "ad hoc" algorithm leading to the relations to be used to determine a possible leak rate.

The basic principle was to check the level of the free surface of the water filling and pressurizing the component: a decrease of this level could have to be indicative of a leakage.

Since many sources other than a leakage could cause a variation of the above level, it needed to anticipate all that could affect this variation in order to arrange all the instruments necessary to measure these parameters and their changes.

So presented the concept is very similar to that which the leak rate measurement of gaseous media is based on (2).

A variation of volume measured by reading the variation of the level of the free surface of the water inside the piezometric container can be related to: 1) a change of the water volume due to any changes of the water temperature and pressure - 2) a change of the internal volume of the Reactor Assembly due to the combined effects of pressure and temperature changes (inside the component). Thus, as first step, it is possible to write:

$$\Delta V_r = \Delta V_m - \Delta V_w + \Delta V_e \quad (1)$$

where:

- ΔV_r is the resultant change of the volume of water which can be indicative of a leakage
- ΔV_m is the measured change of the volume of water
- ΔV_e is the equipment volume change due to a change of walls temperature and inside pressure
- ΔV_w is the variation of the water volume due to a change of its average temperature and its pressure

By the equation (1) the leak rate, L , is given as:

$$L = \Delta V_r / V_{0,w} \quad (2)$$

where $V_{0,w}$ is the initial volume of water.

A variation of the atmospheric pressure value also participates to modify the water volume. So, defined as $(\Delta V / \Delta p)_e$ and $(\Delta V / \Delta p)_w$, respectively, the change of the equipment and the water volumes due to a unitary change of pressure, it is possible to write:

$$\Delta V_e = (\Delta T)_{e,aver.} (\Delta V / \Delta T)_e + \Delta p_w (\Delta V / \Delta p)_e \quad (3)$$

$$\Delta V_w = (\Delta T)_{w,aver.} (\Delta V / \Delta T)_w - (\Delta p_w + \Delta p_{atm}) (\Delta V / \Delta p)_w \quad (4)$$

where:

- $(\Delta T)_{e,aver.}$ is the average change of the equipment temperature
- $(\Delta T)_{w,aver.}$ is the average change of the water temperature
- $(\Delta V / \Delta T)_e$ indicates the equipment volume variation due to a unitary variation of the thermal load
- $(\Delta V / \Delta T)_w$ is the water volume variation due to a unitary change of the water temperature
- $(\Delta p)_w$ is the measured pressure change which can be expressed as:

$$(\Delta p)_w = \gamma_w \Delta H_m \quad (5)$$

being ΔH_m the measured change of the water free surface level and γ_w the specific weight of water

- (Δp_{atm}) is the measured atmospheric pressure change.

The above relationships still held if another fluid in addition to

water (may be liquid or gaseous) is present inside the component. In the case we are discussing about, because of the complexity of the geometry, it wasn't practically possible to be sure that all the air could be vented during the fill up. For this reason the effect of a mass of air had to be taken into account. That could be done simply determining experimentally the parameter $(\Delta V/\Delta p)_f$.

By introducing the relations (3), (4) and (5) in the relation (1) and rearranging, the final relationship to be used to determine if a leakage occurred during the test is obtained:

$$\Delta V_r = \Delta H_m S_p \left(1 + \frac{r_w}{S_p} \frac{\Delta V}{\Delta p}\right) - \Delta V_{f,t} + \Delta V_{e,t} + \Delta p_{atm} \left(\frac{\Delta V}{\Delta p}\right)_f \quad (6)$$

or, in terms of leak rate L: $L = \Delta V_r / V_{o,f}$ (7)

where:

- S_p is the cross section area of the container above the piezometric tube
- $(\Delta V/\Delta p)$ is equal to $(\Delta V/\Delta p)_f + (\Delta V/\Delta p)_e$
- $\Delta V_{f,t}$ is equal to ΔT_f , aver. $\times (\Delta V/\Delta T)_f$
- $\Delta V_{e,t}$ is equal to ΔT_e , aver. $\times (\Delta V/\Delta T)_e$
- K is equal to $(1 + (r_w/S_p) \times (\Delta V/\Delta p))$
- $V_{o,f}$ is the volume of the fluid initially contained inside the component; namely: $V_{o,f} = V_{o,w} + V_{o,air}$. Since $V_{o,air}$ is smaller and smaller than $V_{o,w}$ (as it will be shown by the following discussion), it can be put: $V_{o,f} \approx V_{o,w}$

4 EVALUATION OF THE SIGNIFICANT PARAMETERS

Making reference to equation (6) a set of parameters needed to be determined in the course of the test in order to evaluate if the Reactor Assembly leaked or not. What is following will describe how each parameter has been determined.

A) Evaluation of the volume of fluid initially contained inside the component ($V_{o,f}$)

The volume of water introduced inside the Reactor Assembly was measured by means of a "water meter". A volume of about 87000 liter of water was used to fill up the equipment.

The volume of the air which didn't vent out was determined by means of the same test used to determine the parameters $(\Delta V/\Delta p)$ and $(\Delta V/\Delta p)_f$ of equation (6).

It will be shown later how this evaluation has been carried out. A volume of about 100 ± 140 liter of air has been "measured" at the beginning of both the leak tests.

The initial volume of fluid was perfectly consistent with the calculated overall inside volume of the Reactor Assembly: $V_e = 86935$ liter.

B) Evaluation of the deformability of the Reactor Assembly structure under thermal conditions $(\Delta V/\Delta T)_e$

Three different thermal loads have been recognized to have the possibility to occur during such a test:

- a) a uniform overall change of temperature;
- b) a linear temperature variation at the top of the Reactor Assembly with temperature growing from inside to outside and viceversa;
- c) a linear temperature variation at the bottom of the Reactor Assembly with temperature growing from inside to outside and viceversa.

The volume change caused by each of the above thermal loads has been computed by means of a Finite Elements model of the structure which unitary loads were imposed to.

The following values were obtained:

- Case (a) $(\Delta V/\Delta T)_e = 3.78$ liter/ $^{\circ}\text{C}$
- Case (b) $(\Delta V/\Delta T)_e = 0.069$ liter/ $^{\circ}\text{C}$
- Case (c) $(\Delta V/\Delta T)_e = 0.034$ liter/ $^{\circ}\text{C}$

C) Evaluation of the deformability of the Reactor Assembly under a uniform internal pressure $(\Delta V/\Delta p)_e$

By means of the same above Finite Element model the variation of the internal volume of the Reactor Assembly caused by a uniform unitary pressure acting inside the component has been computed. The value so obtained has been:

$$(\Delta V/\Delta p)_e = 18.95 \text{ liter/bar}$$

D) Evaluation of the average temperature of the Reactor Assembly

During the first leakage test the average temperature of the Reactor Assembly has been determined by means of a certain amount of temperature sensors located at suitable locations on the outside walls and on the upper surface of the second plate of the tested component. The indications of such sensors have been combined with a weighted averaging procedure to get the average temperature of the component.

For the second test it wasn't possible to place again the above temperature sensors. But it was still possible to obtain the variation of the average temperature of the Reactor Assembly since during the first test it was observed a quite perfect correlation between the temperature of the water and that one of the equipment. Based on that, a factor 0.74 was used to obtain the relative variation of the equipment volume from the relative variation of the water volume.

E) Evaluation of the average temperature of water and its thermal volume change $(\Delta V/\Delta T)_w$

The average temperature of the water filling the Reactor Assembly was determined by means of the temperature sensors placed inside the equipment at certain suitable locations.

From their answers, using a weighted averaging technique, the average temperature of the water, T_w , aver., was obtained. Being known the coefficient of thermal expansion of water, hereafter indicated as $(\Delta V/\Delta T)_w$, any changes of the water volume was obtained measuring a variation of T_w , aver.

F) Evaluation of the atmospheric pressure change Δp_{atm}

The atmosphere pressure changes were measured by suitable manometers located in the environment around the Reactor Assembly.

G) Evaluation of the change of the level of the free surface of the water ΔH_m

This amount was measured by means of manometers located in correspondence of the bottom of the transparent container located above the piezometric tube.

H) Evaluation of the overall deformability under pressure $(\Delta V/\Delta p)$

The knowledge of the parameter $(\Delta V/\Delta p)$ resulted to be very important because it represented the only tool to determine the amount of air trapped inside the equipment in spite of it was vented during the fill up.

The overall deformability under pressure was determined simply adding at the water pressurizing the equipment a calibrated amount of water (usually 2 liter) and reading the increase of pressure so obtained. Such an increase is related to:

- the compribility of water itself, $(\Delta V/\Delta p)_w$
- the deformability of the component under pressure, $(\Delta V/\Delta p)_e$
- the compribility of any other fluid eventually present, $(\Delta V/\Delta p)_{o.f.}$

Since the first two parameters were well known, by means of this test it was possible to check if any other fluid be present and, in particular, if it was a gaseous medium or a liquid one: a high value for $(\Delta V/\Delta p)_{o.f.}$ should be indicative of a gaseous medium.

Once established the presence of a gaseous medium (in other words: air) it should be possible to compute its volume simply applying the perfect gases law.

Hypothesizing that the air, essentially confined at the top of the Reactor Assembly, experiences an isothermal compression when adding a calibrated amount of water, we can find:

$$V = - p (dV/dp)_{air} \quad (8)$$

from which, once known $(dV/dp)_a$ and p , the air volume can be found. Performing such a test at the beginning, during and at the end of the

leak test the evolution of the confined volume of air should have been possible to be determined.

5 SOFTWARE DESCRIPTION

The various parameters are scanned and measured by the acquisition system. A computer program has been drawn up for the equations (6) and (7): the various electrical parameters have been transformed into physical values and the experimental or calculated values introduced where necessary.

The volume of water has been divided in "n" elementary volumes V_{iw} each associated to a temperature sensor T_{iw} : the ponderation coefficients C_{iw} relative to every elementary volume

$$C_{iw} = v_{iw} / \sum_1^n V_{iw} \quad (9)$$

have been consequently introduced. The mean averaged temperature is then

$$T_{av} = \sum_1^n C_{iw} T_{iw} \quad (10)$$

The water volume change due to the mean average water temperature (T_{av}) has been determined by means of the Landesen formula:

$$\Delta V_w / V_{0,w} = \alpha T_{av} + \beta T_{av}^2 + \gamma T_{av}^3 + \delta T_{av}^4 \quad (11)$$

The final leak is obtained from a mean square fit line of the form:

$$\Delta V / V = A_0 + A_1 \cdot H \quad (12)$$

where H is the time elapsed expressed in decimal hours. The standard deviation δ_r and the amount of data are then considered to determine the confidence interval.

6 ERROR ESTIMATION

The measurement of a leak rate test is influenced by various types of errors.

Some are of instrumental origin, depending on the quality of the measuring device: resolution, precision or sensitivity, repetitiveness, stability. Others are subordinate to the uncertainty on measured parameters, for instance: the temperature of a sensor is not exactly equal to the mean temperature of the associated volume and the difference is the "representativity error". Some others are of a random nature (resolutions of data or local variations of measured parameters) and are correctly estimated through a statistical analysis. Others are systematic and should be appreciated from the conditions of measurement and calibration.

6.1 Measurements of water temperature

The error on resolution and precision of thermal sensors has been found very low (0.01 l/day) and the random error from statistical analysis of the same order (0.02 l/day). The error of stability which was felt to be preponderant at the beginning has been found through an adapted calibrator, to be of the order of 0.001 °C corresponding to 0.02 l/day. The addition of both errors leads to a value of 0.03 l/day.

From our experience, in that field the representativity error is by far more important than the above. That is due the fact that the water temperature variations are measured by means of a reduced number of sensors: depending on this number the obtained value is more or less representative of the mean water temperature.

To assess this last one, to every sensor has been attributed a ponderation coefficient depending on the associated volume. From the results it appeared that the temperature evolution was very regular and a "stratification" set up. The representativity error could be reckoned in an unfavourable way assuming that the parameter $\Delta V_w/V_{0,w} = f(T_w)$ be get by the data of only one sensor. So proceeding the parameter $\Delta V_w/V_{0,w} = f(T_w)$ for the last twenty four hours of pressure level was in the range:

$$0.575 < \Delta V_w/V_{0,w} < 1.062 \text{ (l/day)}$$

with a confidence interval of $0.326 < 2\delta_r < 0.31 \text{ (l/day)}$

If one makes the pessimistic assumption that every sensor indicates the temperature of the associated volume with an error corresponding to the global scattering of the whole sensors, the resulting error on the mean of 14 sensors is for both the test: $0.326/\sqrt{14} = 0.08 \text{ l/day}$. The same estimate made on the wall measured temperatures during the first test has shown that the error on the vessel volume is negligible.

6.2 Measurement of pressure

Due to the great sensitivity of the pressure transducers, the random error due to the electrical resolution is negligible.

The precision on the site calibration is of the order of 0.1%. So an initial estimate of +/- 2l variation would lead to a value of 0.02l. The stability of measurement had been specified by the manufacturer to reach a maximum of 0.6 mbar (0.024 l/day). During the test a value of only +/- 0.2 mbar was found (corresponding +/- 0.008l). The error on ΔH was also very low (0.4 mbar = 4 mm of water).

6.3 Total error

The main errors evaluated hereabove have no reason of having the same sign: consequently a conservative value of the global error may be

obtained by adding the absolute values of all the partial errors (approximately the same for both leak tests):

$$e_{\text{tot.}} = 0.02 + 0.01 + 0.03 + 0.08 = 0.14 \text{ l/day}$$

The moderate value of the instrumental error shows the degree of accuracy on which it can be relied in the measurement of a leak rate on large vessels under test pressure.

However it will be shown in the following paragraph that the uncertainty of measurement was due mainly to "secondary" phenomena, such as the inopportune presence of a large air volume at the top of the vessel, whose behavior is difficult to be appraised with precision due to the complexity of the involved phenomena (absorption, and so on).

7 RESULTS AND THEIR INTERPRETATION

7.1 Overall deformability of the system under pressure ($\Delta V/\Delta p$)

The parameter ($\Delta V/\Delta p$) has been evaluated at the beginning, during and at the end of each leakage test.

Making reference to the same value of pressure with respect to the top of the Reactor Assembly, approximately 2.10 bar (at the level of the second plate); the values of ($\Delta V/\Delta p$) at the beginning and at the end of each test were:

First leakage test: ($\Delta V/\Delta p$) = 86.96 l/bar at the beginning
= 81.70 l/bar at the end

Second leakage test: ($\Delta V/\Delta p$) = 69.54 l/bar at the beginning
= 65.17 l:bar at the end.

In the above values the contribution of the deformability under pressure of the structure and the deformability under pressure of the water filling the Reactor Assembly is contained too. Because these last amounts had been already determined (being ($\Delta V/\Delta p$)_e = 18.95 liter/bar (from F.E. analysis) and ($\Delta V/\Delta p$)_w = 3.50 liter/bar) the contribution of the structure and water together was: ($\Delta V/\Delta p$)_{e+w} = 22.45 liter/bar.

The difference among this last value and the ones experimentally determined could be explained only with the presence of a very compressible medium as a gas (on this point of view the most credible one was considered to be air trapped inside the component during the fill up). An independent confirmation of the presence of air at the top of the equipment was got by the temperature sensors located inside the component and on the top of the upper plate (these last ones for the first test only). Diagraming the temperature vs. time a very rapid oscillatory change of the temperature just below the upper plate following the oscillatory change of the room temperature could be observed: such a phenomenon is indicative of the presence of a

Even if the analytical results appear to be scattered over a wide range (essentially because of the complexity of the phenomenology under investigation and the uncertainties of the input data) they give an important confirmation that such a phenomenon occurred and also played a significant role.

Essentially based on these reasons the results of both the leakage tests were judged positive and the tightness of all the joints demonstrated.

8 CONCLUSIONS

The leak test herein described was peculiar since used water as test medium nevertheless the welded joints were not inspectable.

The use of a liquid caused that a particular procedure to analyze and interpret the results be tuned up. In particular a specific test to check if air, and its amount, had been trapped inside the component during the fill up was conceived.

A decrease of the air volume during the test was demonstrated to be occurred. Due to this decrease it was demonstrated the "apparent" leak rate measured was to be related to. To explain the decrease of the air volume during the test the absorption of air by water has been shown to play a significant role.

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