STATISTICAL ANALYSIS OF THE LEAK RATE MEASUREMENTS OF REACTOR CONTAINMENTS

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SUMMARY

This paper relates the results given by the statistical analysis of the leak testing measurements of five prestressed concrete containment vessels.

A high degree of confidence in the "absolute method" had been gathered from our measurements on steel vessels since 1964. The modern computer-based data acquisition and treatment systems now permit intensive use of statistical methods for better calibration and better data analysis. A very good mathematical accuracy can be obtained, but the results could be misleading without a thorough basic study of the physical phenomena involved in the transducers as well as in the containment behaviour.

1. For each set of measurements, taken every 1/4 of an hour, the four parameters of the following basic law are calculated

$$\frac{DM}{M_0}=\frac{DP}{P_0}-\frac{DP_V}{P_0}-\frac{DT}{T_0}.$$

The first outcome consists in displaying a plot of the four parameters, and carrying out a general linear regression analysis between DM/M_0 and the time. The second and more interesting analysis is a linear regression for the last seventeen sets of measurements, i.e. four hours. This calculation provides an estimation of the mean slope of the tangent to the plot of every parameter. It gives also the residual standard error, which is an estimation of the equivalent resolution of the measurements.

2. The absolute pressure transducers were two quartzgauge manometers. Residual standard error on DP/P_0 amounts to 3.10^{-6} or 0.015 mba. A verification test was performed by introducing in the containment a defined amount of nitrogen in 6 hours. The corrected leak rate variation after correction by the nitrogen weight did not exceed ±0.008% a day from the last 4 hours of the main test.

3. The temperature transducers consisted of platinum resistances cemented on aluminium cylinders. 58 transducers were placed in the containment. The residual standard error was $1.2.10^{-5}$, which corresponds to a confidence interval on the mean value of air temperature of about ±0.007 °C. Convincing verifications of temperature representativity were carried out by starting a motor in one little cell, or by putting in and out the general lightning in the containment.

4. The vapour pressure transducers were lithium chloride hygrometers. Six hygrometers were placed in the containment. The best verification results from a "zero leak test" performed at atmospheric pressure after having scavenged the containment with dry air. In this test, the main variation was a fast raise of the vapour pressure. As the leak under null pressure difference must be zero, the DM/M_0 results are mainly attributable to hygrometry measurements: the error was about 2 to 5% of the water vapour pressure variation.

0. Introduction

The leaktightness of a containment vessel is a major feature of nuclear power plants safety.

For the 900 MW PWR series, the allowable leak rate at design pressure (5 bars absolute) is about 0.2 % per day of the total mass of air in the containment. This low value is possible through the fitting of a metallic liner, inside the prestressed concrete wall, and by performing local leakage rate measurement at the point of the containment electrical penetrations, access hatch penetrations, and isolation valves of fluid pipings penetrating into the containment. The effectiveness of these procedures is verified by performing integrated leak rate testings, first as preoperationnal testing, then as periodical testing. These tests have to be carried out with a great accuracy, as 0.2 % per day is equivalent to a pressure change of about 10 mbars, or mean temperature change of about 0.6°C.

Between December 1975 and October 1976, Bureau Veritas has performed the preoperationnal testing on the containment vessels of Nuclear Plants Fessenheim 1 & 2 and Bugey 2. One of them had to be retested, and another leak testing was achieved upon a prestressed concrete vessel without liner. Some results of these 5 testings are presented in this paper, to give an idea of the accuracy of the method.

1. Test Method

1.1 The test method used is the Absolute Method, in which the pressure, temperature, water vapor pressure measurements are analysed by the Mass-Plot Analysis Method [1]

This method was used by Bureau Veritas as far as 1963, to determine the leak rate of bare steel containments [2] . Such containments show very large changes in temperatures and pressures (see Fig. Nr. 1). In four of these tests, the Reference Vessel Method was used by other organisms : in each case, their results were less reliable than ours for the following reasons : insufficient leak tightness of the reference vessels, or differences between the mean temperature of the vessels and the mean temperature of the air.

1.2 The derivative of the perfect gas law applied to the dry air gives the following basic rough formula

$$\frac{DM}{M} = \frac{DP}{P} - \frac{DPv}{P} - \frac{DT}{T} \qquad (1)$$

The exact value of each term is

$\frac{DM}{M} = \frac{M - Mo}{Mo}$ relative loss of dry air mass between moment 0 and moment H

$\frac{DP}{P} = \frac{P - Po}{Po - Pvo}$ relative loss of dry air pressure

The last two terms are mean values, calculated from the following constant volume weight coefficient c_i

$$c_i = \frac{\frac{v_i}{T_{io}}}{\sum_1^n \frac{v_i}{T_{io}}}$$

the containment being parted in n volumes "vi" ,

$$\frac{DPv}{P} = \frac{\sum c_i (P_{vi} - P_{vio})}{P_o - P_{vo}}$$

$$\frac{DT}{T} = \sum c_i \frac{T_i - T_{io}}{T_i}$$

$$P_{vo} = \sum c_i P_{vio}$$

with

T_i = absolute temperature of the Volume V_i

P_{vi} = vapor pressure in the volume V_i

P = total absolute pressure

These formulas give the exact value of mass variation, even when large temperatures differences exist, as in periodical testing.

1.3 Each set of measurements is automatically recorded every 1/4 of an hour by the data acquisition system. The programmable calculator stores the data in a cassette, executes immediately the calculation of the four basic parameters $\frac{DP}{P}$, $\frac{DT}{T}$, $\frac{DPv}{P}$ and $\frac{DM}{M}$, and plots the results with respect to the time elapsed from the beginning DH.

The Figure Nr. 1 shows the similar graph obtained in 1965 during a 36 hours test on the steel containment vessel ESSOR at Ispra (Italy). The diurnal pressure variations are correctly compensated for temperature and water-vapor pressure changes, as no correlation exists between the pressure maxima and minima, and the $\frac{DM}{M}$ maxima and minima. The maximum error is about ± 0,1 % and results from high temperature gradients.

The Figure Nr. 2 shows the graph obtained during the testing of the first PWR containment This is an almost ideal set of results, as the 96 values of $\frac{DM}{M}$ are perfectly located on a straight line without any influence of the curvature of temperature and pressure evolutions.

1.4 On line statistical analysis is performed by calculating the linear least squares fit defined by

$$\frac{DM}{M} = A_0 + A_1 \, DH \qquad (2)$$

When expressed in percentage per day, the value of the measured mean leak rate is $L_M = 2{,}4.10^3 . A_1$ together with its 95 % confidence interval, IC.

The Residual Standard Error, SR , gives an estimation of the distribution of the points around the straight line. In the example shown in Fig. Nr. 2, the distribution is random, and clearly results from the random distribution of the points around the temperature curve. S_R value is $1{,}2.10^{-5}$, which corresponds to errors of :

± 0.007°C on the mean temperature of 48 000 M3 of air

or ± 0.12 mba on the pressures.

The 95 % confidence interval on the L_M estimation is ± 0,001 % per day, which represents about 0,5 % of the allowable value, giving a fairly precise estimation of the leak rate. In fact, this is only the random part of the error to which should be added systematic errors which are :

- the sensitivity errors of the measurements ;
- the representativity errors of the weighting coefficients.

These errors are obviously small, in this case, as otherwise a certain amount of the curvature of $\frac{DP}{P}$ or $\frac{DT}{T}$ would be present in the evolution of $\frac{DM}{M}$.

It must be noted that, when the temperature and pressure evolutions are linear, it is possible to use wrong sensors sensitivities or wrong weighting coefficients, and to obtain a very small confidence interval. This is the case when circulating fans are used inside the containment, or when the test time is too short : the confidence interval can be very small, but centered on a wrong leak rate value.

1.5 In most cases, the points are randomly distributed not along a right line, but along a curve. In this case, the confidence interval on the mean slope, and the mean slope itself, have no signification in safety terms.

As an example, the equation

$$\frac{DM}{M} = - 4{,}17.10^{-5} \, (DH)^2 \qquad (3)$$

represents a curve with constant curvature, having a tangent slope of 0 at DH = 0, and 0.2 % per day at DH = 24.

The least square fit gives a leak rate of −0.1 % per day. The 95 % confidence interval is ± 0,0053 % per day, which can be considered as a good accuracy.

In fact, such a curve can be the result of a strong outgassing concealing a leak rate greater than the allowable limit, and far from the calculated confidence interval.

1.6 The basic reason of such a discrepancy is that statistical methods must be applied only to randomly distributed results.

This is the case if the least square fit is performed on a period of time short enough to have curvature effects smaller than the random scatter.

Therefore, a second statistical analysis was performed to calculate an "instantaneous leak rate" from the last 17 measurements, corresponding to the last 4 hours.

The Table Nr. I corresponds to the end of the test whose plots are shown in Fig. Nr. 2. It shows for each moment DH the instantaneous leak rate value L_M, with the residual standard error S_R, the 95 % confidence interval IC, and the limits of the confidence interval, LS and LI.

At the end of the test, statistical analysis of the 96 L_M values give the mean value and the confidence interval of the L_M values : it is practically equal to the mean value of the 96 values of IC. This confirms that the $\frac{DM}{M}$ are randomly distributed along a straight line.

The confidence interval from random errors on a 4 hours leak rate is about ± 0.01 % per day, which looks as a sufficient accuracy to detect if the leak rate is constant or not.

1.7 When the same calculation is made on the constant curvature equation mentioned above in 1.5, the results are :

DH = 0 to 4 hours : $L_M = -0.017$ % ± 0.0024 % per day
DH = 20 to 24 hours : $L_M = -0.183$ % ± 0,0024 % per day

The confidence interval from curvature is significantly smaller than the random one.

The leak rates are equal to the slopes of the tangent line at the middle point of the respective 4 hours.

Therefore, this procedure seems a good compromise to measure with a sufficient accuracy the "instantaneous leak rate" (referenced hereafter as ILR).

A detailed analysis of these instantaneous leak rates in the whole testing permits to give sound explanations of the variations, so that the real leak rate can be estimated.

1.8 To explain soundly the variations of the measured leak rate, it is necessary to have a precise idea of the measurements accuracy, not only from laboratory tests, but rather from field measurements, analysed by the same statistical methods.

This is the scope of the next chapters.

2. Pressure measurements

2.1 The pressure transducers are two quartz absolute manometers.

The signal fed into the data acquisition system represents directly the pressure variation, the servo mechanism being stopped at the beginning of the test, just after closing the air inlet or outlet valve. A specific method has been devised to filter and calibrate this signal, which is noisy and non linear.

2.2 Use of statistical methods for calibrating gives a sensitivity accuracy better than ± 0.1 % for pressure changes of ± 30 mbars.

The electrical resolution of the measurement corresponds to ± 0.0025 mba.

When a least square fit is proceeded on linear pressure variation of the containment $\frac{DP}{P}$, during tests at the design pressure, the residual standard error is about $3,1.10^{-6}$, corresponding to a"practical resolution" of $\pm$ 3.1×10^{-6} x 2 x 5,ooo = $\pm$ 0.031 mba.

The corresponding 95 % confidence interval on the "instantaneous leak rate" calculated on 4 hours is ±0,003 % per day.

The stability of the signal against thermal or electrical disturbances or vacuum losses is verified by comparing the pressure variation given by the two pressure transducers, which have a different sensitivity under these effects. Statistical analysis of their difference leads to instantaneous L.R. (I.L.R.) from pressure transducers drift (mainly due to ambient temperature changes) of about ±0,01 % per day at design pressure. This corresponds to a drift of ±0.08 mba in 4 hours which is about the zero drift announced by the manufacturer for ± 4°C ambient temperature change.

For periods of time over 4 hours, the effect on leak rate is smaller.

2.3 A verification test was made by introducing a weighted amount of nitrogen into the containment, in 2 or 6 hours. The Fig. Nr. 4 shows in part 1 the results of such a test :

- the pressure parameter $\frac{DP}{P}$ shows a slope change of 0.18 % per day ;
- the mass parameter $\frac{DM}{M}$, corrected for the variation of the nitrogen cylinders mass,

has a linear evolution, within instantaneous leak rate random variations of ± 0.01 % per day.

As the containment volume is used in this correction, such a test gives a verification of the value of the containment volume rather than a verification of the pressure transducers which are more accurate.

3. Temperature measurements

3.1 The temperature sensors have been specially designed to integrate both the local air temperature (convection) and the wall temperature (radiation) so that their own temperature be closer to the mean temperature of the volume.

They consist in platinum resistances cemented on an aluminium cylinder. They were calibrated against standard platinum resistance thermometers, from 0°C to 60°C, within ± 0,1°C.

The least square fit method was used to obtain a precise second order law in this domain:

$$T = A_0 + A_1 \frac{DR}{R} + A_2 \frac{DR}{R} \qquad (4)$$

A_0 was adjusted for each sensor

A_1 and A_2 were the mean values. The individual law of each sensor being within ± 0.3 % of these mean values, it is felt that the chosen law permits an accuracy better than ± 0,3 % on temperature changes.

Balancing circuits and wiring are based on our long experience of field strain gaging with a minimum number of long wires of minimum section, but with high electrical stability : the microstrain unit is equivalent to 5.10^{-4}°C.

The electrical resolution of the measurement is $\pm 2 \times 10^{-4}$°C.

3.2 58 temperature sensors were installed in each containment vessel.

This number is higher than generally used in such PWR vessels, and was chosen after a study of the thermal heterogeneity during the periodical testing. During these periodical testings, some circuits may be stopped or started and as some of them are disposed in ternary symetry, each of the three corresponding zones can be thermally affected.

The efficiency of such a disposal has been demonstrated by starting a pump in the smallest room instrumented, about 168 M3, or 0.35 % of the containment volume. The Fig. Nr. 3 shows in part 2 the result of this operation. After a 6 hours verification test, the motor of RRA pump (cooling of the reactor during shut down) was started. The local heating gave a rise of the general pressure $(\frac{DP}{P})$, which was well corrected by the temperature measurements $(\frac{DT}{T})$ so that, except for the first 3 points, the mass plot is aligned with the previous calculations.

The highest local temperature variation was, in the room containing the motor, about 2.7°C. This variation is 22.5 times greater than the consecutive general variation, so the importance of this small cell is actually about $0.35 \times 22.5 = 7.9$ % of the total volume.

This confirms the necessity, for periodical testing, to have sensors in the smallest room where hot points can be started or stopped, and justify the number of sensors.

4. Water vapor measurements

4.1 The first tests were made with capacitive hygrometry sensors which were claimed to be sturdy and reliable. A lot of troubles was experienced with these devices : erratic behaviour at high hygrometry, ambient temperature sensitivity of the meter, etc..

It was necessary to design a new type of electrical circuit and to perform intricate calibration tests, as the sensor itself is sensitive to the ambient temperature.

4.2 The Lithium Chloride sensors have the advantage of giving directly the water vapor pressure (and not the hygrometry) from temperature measurements by platinum resistance.

Individual calibration gave cubic laws with coefficients within ± 5% from one sensor to another.

4.3 Only six water vapor sensors were used. It was first supposed that these measurements would have a low precision, and that they could be used to verify that the water vapor changes were small, rather than to correct large changes in hygrometric situation.

The Figure Nr. 4 shows a check of the water vapor measurements by Lithium Chloride sensors, performed during a test at zero pressure. In such a test the leak rate must be practically zero, as there was no differential pressure between containment and atmosphere.

It can be seen that the vapor pressure change, about 0.32 % per day, is correctly measured giving a leak rate of +0.007 % per day, with a 95 % confidence interval of ± 0.007 % per day. Therefore the error on vapor pressure measurement is smaller than $\frac{0.007}{0.320} = 2$ %.
With capacitive sensors, errors as high as 5 % have been found for the same type of test.

5. Results

5.1 The Table II presents the leak rates measured during the four testings of PWR containment vessels. The values are the mean leak rates in % per day, resulting from 8 hours long measurements. They are taken when pressurizing (arrow ↗) or depressurizing (arrow ↘) the containment vessel. Some correspond to the first 8 hours (after initial stabilization), others to the last 8 hours of 24 hours measurements.

Positive value means an air inlet, or outgassing (see 5.3).

Negative value means a leak or ingassing (see 5.3).

5.2 Accuracy

To compare soundly the different results, it is necessary to evaluate the possible errors.

The main error seems to be a drift of the pressure transducer, assumed to be 0.01 %

per day for a 4-hour test at design pressure. If this drift is supposed to be randomly distributed and independant of pressure, the error for a 8-hour measurement is 0.007 % per day at design pressure, and 0.014 % per day at half design pressure.

The error from random part of measurement is also about 0.01 % per day for a 4-hour test at designpressure. It is mainly due to temperature scatter, and is independent of pressure, For a 8-hour test at any pressure, it will be $\frac{0.01\ \%}{2\sqrt{2}} = 0.0035$ % per day.

The error from sensitivity and representativity of the transducers is relatively small, and practically negligible, as it works upon very small changes of pressures and temperatures.

So the accuracy of the values presented in the table nr.II is about

± 0.0105 % per day at design pressure

± 0.0175 % per day at half design pressure.

5.3 Ingassing and outgassing

When a containment is pressurized rapidly, air leaks occurs between the containment volume and small voids in the concrete, or vessels and circuits being inside or outside the containment. When those voids or vessels have the same pressure as the containment, these leaks vanish.

The opposite feature occurs when the containment has been depressurized rapidly.

This results in higher leak rates when pressurizing and lower leak rates when depressurizing, the effect being especially high at the beginning of the tests.

The Table II shows clearly that a phenomenon such as the one described is present in each test. It is possible to make quantitative assessment of such phenomenon by assuming a laminar leakage between the containment volume V_1 , pressure P_1 , and an unique closed volume V_2 , pressure P_2.

The mass flow is governed by the following law :

$$q = K\left(P_2^2 - P_1^2\right) = \frac{dP_2}{dt}\ \frac{V_2}{RT} \tag{5}$$

During pressurizing or depressurizing, it is possible to calculate the pressure $P_2(t)$ from the formula

$$\frac{dP_2}{dt} = \beta\left[P_2^2 - P_1^2\,(t)\right] \tag{6}$$

by assuming an hypothetical value to the parameter $\beta = \frac{K\ R\ T}{V_2}$

After closing the inlet or outlet value, the ingassing or outgassing is determined by the equations (5) and the following

$$q = \frac{d\left(\frac{DM}{M}\right)}{dt}\ \frac{P_1\ V_1}{R\ T} \tag{7}$$

The solution of this system is :

$$\frac{DM}{M} = \frac{V_2}{V_1}\ \frac{P_2 - P_1}{P_1}\ \frac{1 - e^{-2\beta P_1 t}}{1 - \frac{P_2 - P_1}{P_2 + P_1}\, e^{-2\beta P_1 t}} \tag{8}$$

where P_2 is the initial value given by the previous calculation.

This law $\frac{DM}{M} = f\,(t)$ can be compared by the least square fit method to the experimental one. The best value of β is the one giving the minimum residual standard error S_R.

The following table gives the results of such calculations made for the three containment vessels, from the maximum outgassing conditions

Containment →	F_1 bis	F_2	B_2	Units
P_1	0	P/2	P/2	Bars
β	0.10	0.006	0.017	
$P_2 - P_1$	0.427	0.42	0.54	Bars
V_2	120.3	220.4	86	M3
S_R	1.21	1.80	0.57	10^{-5}

The S_R values are of the same order as the ones found in the best linear fit. This seems to confirm the validity of the assumptions made.

The parameters β and V_2 can be used to calculate ingassing and outgassing during the other tests at different pressures : the results were in accordance with the experimental results, within the limits given by the accuracy estimated in 5.2.

These theoretical calculations show that outgassing and ingassing expressed in leak rates are greater at low pressure than at high pressure, and that pressure changes of 0.15 P have a smaller effect than 0.5 P.

5.4 Pressure effects on leak rate

The theoretical pressure effect on the leak rate through constant leakage path is given by the formula

$$L_M = K \frac{(P^2 - 1)^{\alpha}}{P}$$

P is the absolute pressure in atmospheres ($\sim$1 bar)

Exponent α is 1 for laminar flow and 0.5 or 0.4 for turbulent flow.

When testing at different pressures a prestressed concrete vessel without liner, one could measure the leak rate with great accuracy, as it was 90 times greater than the allowable value for PWR containment.

The value of α was 1.09 from the measurements preceding the peak pressure, and 0.72 from the measurements following the peak pressure. The laminar flow rule seems to fit these results in a better way than any other. An exponent greater than 1 indicates some effect of opening of the leak path at high pressure. An exponent smaller than 1 indicates that a part of this high leak is turbulent.

For PWR containments, the leak rate ratio between design pressure and half design pressure would be 1.8 for laminar flow and about 1 for turbulent flow.

The last three PWR containments had very small leak rates, and the relative accuracy is too low to give a valuable ratio with pressure change.

However, it can be clearly seen that F_2 tests give a higher leak rate at half pressure than at design pressure. This can be caused by some closures being tighter with higher differential pressure.

The leak rates of the first containment were relatively more accurate, and the ratio is $\frac{0.234}{0.164} = 1.43$, with 1.23 and 1.67 as limits from measurements accuracy.

We think that in this case the laminar ratio of 1.8 has been lowered by some self lock effect, rather than by turbulent flow effect, which is less probable for low leak rates than for high leak rates.

6. Conclusions

6.1 The first conclusion which proceeds from these tests is the very satisfactory tightness of the first three PWR nuclear plants containment vessels determined through preoperational tests.

This fact shows that the intensive procedure of previous check of local tightness recommended by Electricité de France has proved to be efficient. This is also quieting for the holding of the tightness during working condition.

6.2 As the leak rate to measure was very small, it was possible through an improved statistical analysis to have an objective knowledge of the errors due to the instrumentation, or to any other phenomenon.

6.2.1. The total accuracy for a preoperational 8-hour test is ranging about ± 0.01 % per day for the design pressure and ± 0.0175 for half this pressure. This precision will likely be maintained through periodical test.

6.2.2. Errors lower than ± 0.1 % per day may be found at beginning of test due to outgassing or ingassing of cells (voids in concrete or closed circuits) amounting to 100 cubic meters: these effects decrease noticeably with time, which could be settled through a 24-hour leak variation analysis.

6.2.3. The action of pressure on the leak rate variation conforms probably to the laminar flow law, accompanied sometimes by a more or less marked self-lock effect. The ratio between the full pressure and half pressure leaks is consequently lower than if obtained through the laminar flow law.

3. For the preoperational test, the best procedure, according to our experience, lies in :

a) Dry air scavenging during 24 hours. Pressurizing and depressurizing performed at the same rate.
b) Tests during 8 hours at least at every pressure stage : 0 - 0.5 P - P - 1.15 P - P - 0.5 P - 0.
c) Extension of the test period up to 24 hours for the first stage at 0.5 P and the second one at P. If large differences are found between the first and second test at 0.5 p, this latter test should be carried on for 24 hours.
d) Extension of the test period to 16 hours for the first stage at P.

During the last 8 hours one will try to obtain local and general heating.

This procedure allows a complete check of the whole measuring equipment.

6.4 For periodical tests, a 8-hour test at 0.5 P is deemed to be sufficient as the vessel should be normally very tight and the extrapolation at P of the leak at 0.5 P through the laminar flow law - all errors added - will lead to a value in excess, taking in account the unfavourable outgassing effect. If this latter is exaggerated, the test extension becomes necessary.

References

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TABLE I

LEAK RATES FROM 4 HOUR-MEASUREMENTS

```
      H          % 24 H        10^-3       %'24 H        % 24 H        % 24 H

DH= 18.89   LM= -.230   SR=  .012   IC=  .012   LS= -.242   LI= -.218
DH= 19.14   LM= -.225   SR=  .012   IC=  .012   LS= -.238   LI= -.213
DH= 19.39   LM= -.225   SR=  .012   IC=  .012   LS= -.238   LI= -.213
DH= 19.64   LM= -.230   SR=  .012   IC=  .012   LS= -.241   LI= -.218
DH= 19.89   LM= -.231   SR=  .011   IC=  .011   LS= -.243   LI= -.220
DH= 20.14   LM= -.232   SR=  .011   IC=  .011   LS= -.243   LI= -.221
DH= 20.39   LM= -.235   SR=  .012   IC=  .011   LS= -.247   LI= -.224
DH= 20.65   LM= -.232   SR=  .011   IC=  .011   LS= -.243   LI= -.221
DH= 20.90   LM= -.233   SR=  .011   IC=  .011   LS= -.244   LI= -.222
DH= 21.15   LM= -.240   SR=  .011   IC=  .011   LS= -.251   LI= -.229
DH= 21.40   LM= -.240   SR=  .011   IC=  .011   LS= -.251   LI= -.229
DH= 21.65   LM= -.242   SR=  .011   IC=  .011   LS= -.253   LI= -.231
DH= 21.90   LM= -.238   SR=  .012   IC=  .011   LS= -.249   LI= -.226
DH= 22.15   LM= -.236   SR=  .011   IC=  .011   LS= -.247   LI= -.225
DH= 22.40   LM= -.226   SR=  .013   IC=  .013   LS= -.239   LI= -.214
DH= 22.65   LM= -.230   SR=  .013   IC=  .013   LS= -.243   LI= -.218
DH= 22.91   LM= -.233   SR=  .012   IC=  .012   LS= -.245   LI= -.221
DH= 23.16   LM= -.231   SR=  .012   IC=  .012   LS= -.243   LI= -.218
DH= 23.41   LM= -.231   SR=  .012   IC=  .012   LS= -.243   LI= -.218
DH= 23.66   LM= -.231   SR=  .012   IC=  .012   LS= -.243   LI= -.219
DH= 23.91   LM= -.233   SR=  .013   IC=  .013   LS= -.245   LI= -.220
DH= 24.16   LM= -.233   SR=  .013   IC=  .013   LS= -.245   LI= -.220
DH= 24.41   LM= -.232   SR=  .012   IC=  .012   LS= -.244   LI= -.219
DH= 24.66   LM= -.234   SR=  .012   IC=  .012   LS= -.246   LI= -.221
DH= 24.91   LM= -.234   SR=  .012   IC=  .012   LS= -.246   LI= -.221

    LM (M0YEN)= -.230   2S=  .009
```

TABLE II

LEAK RATES IN % PER DAY

from 8 hour - measurements

▭ best estimates of leak rates

Pressure	P/2		P		1,15 P
Containment	Beginning	End	Beginning	End	
F_1 ↗	-0,223	$\boxed{-0,164}$	-0,248		-0,303
↘	-0,070		-0,225	$\boxed{-0,234}$	
F_1bis ↗	-0,017	$\boxed{-0,006}$	-0,026	$\boxed{-0,021}$	
F_2 ↗	-0,051	-0,030	-0,042		-0,027
↘	+0,047	$\boxed{-0,032}$	+0,019	$\boxed{-0,007}$	
B2 ↗	-0,076		-0,035		-0,032
↘	0,051	0,010	0,005	$\boxed{-0,010}$	

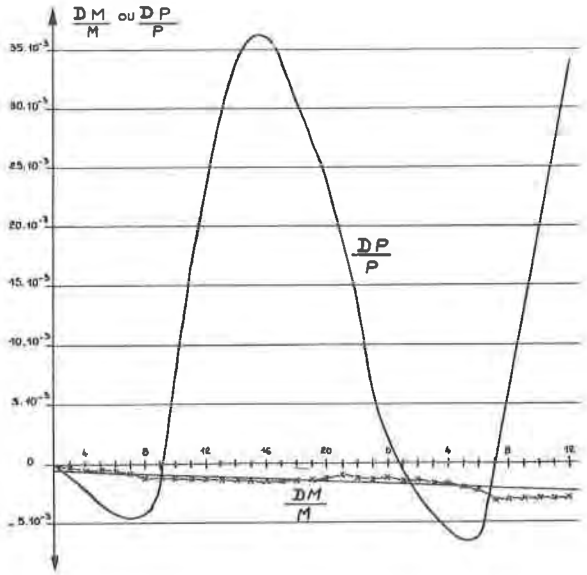

Figure 1 Leak testing of ESSOR containment vessel at Ispra (Italy) , 26 and 27 May 1965

P = 0,25 bars V = 50,000 m3

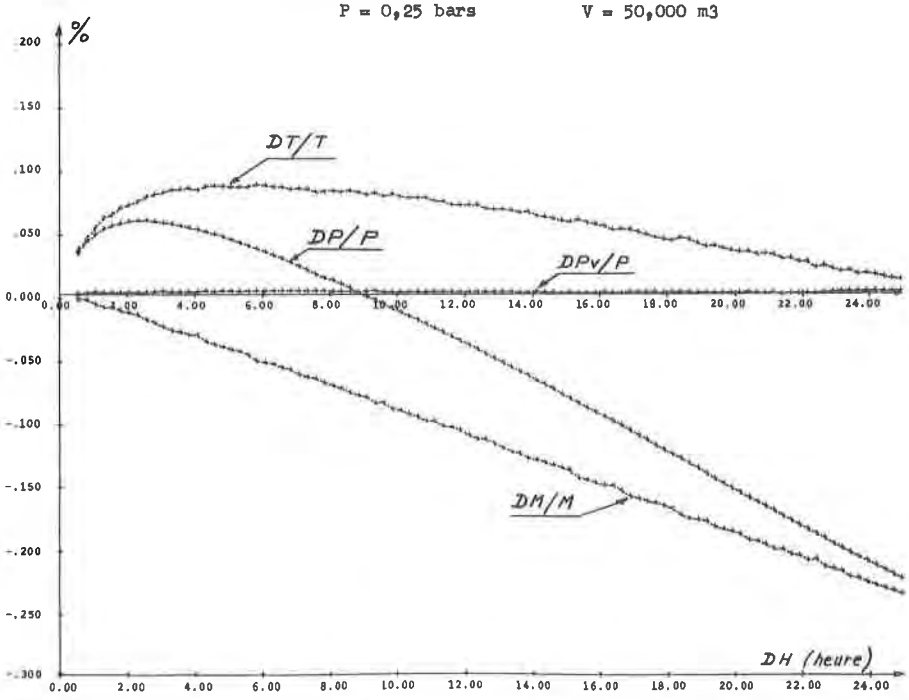

Figure 2 24-hour test at design pressure

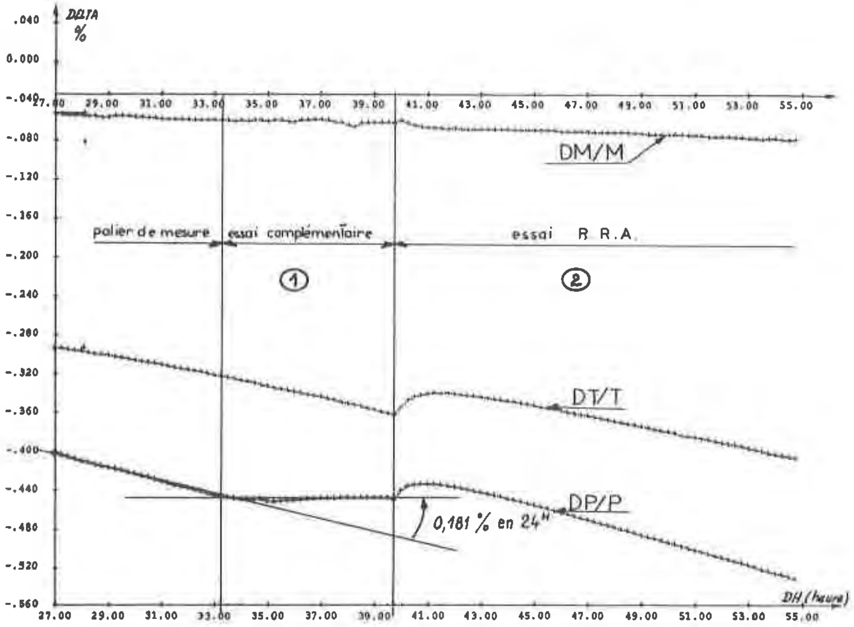

Figure 3 1 **Verification test**

2 **Test with local heating**

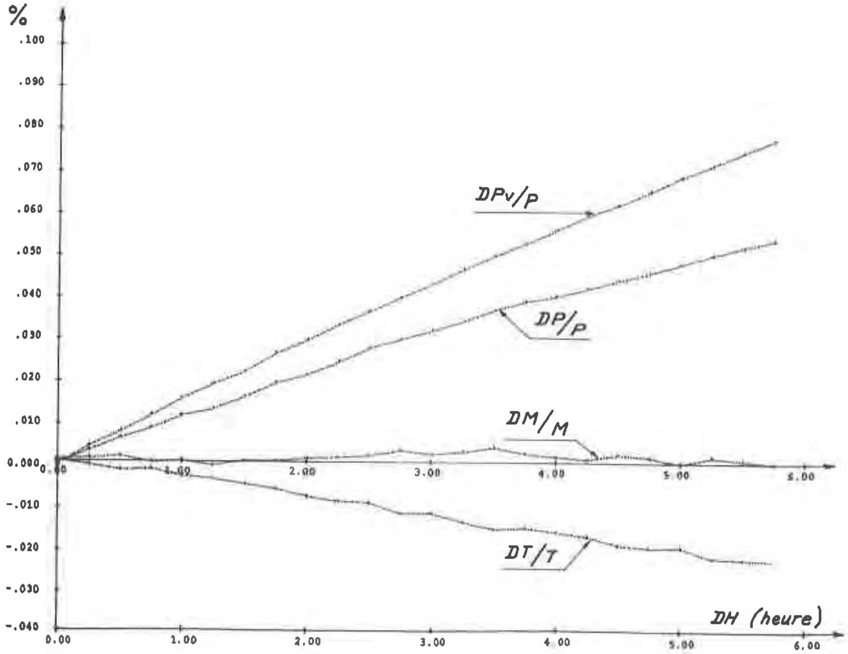

Figure 4 **Test at atmospheric pressure**