TRANSACTIONS OF THE 9TH INTERNATIONAL CONFERENCE ON
STRUCTURAL MECHANICS IN REACTOR TECHNOLOGY / LAUSANNE
17-21 AUGUST 1987

# Structural Mechanics in Reactor Technology

*Editor*
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OFFPRINT

A.A.BALKEMA / ROTTERDAM / BROOKFIELD / 1987

# 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 (see, Figures 1(a) and 1(b)) 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 (particular 14 of Figure 1(a)) 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 peculiarprocedure 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 as schematically shown in Figure 2. 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 any variations of the water free surface level could cause a significant variation of pressure, so modifying the test pressure value.
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 (See, Figure 3). 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 (see, Figure 4).
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). As first step, it is possible to write:

$$\Delta Vr = \Delta V_m - \Delta Vw + \Delta Ve \qquad (1)$$

where:
- $\Delta$ Vr is the resultant change of the volume of water which can be indicative of a leakage
- $\Delta$ Vm is the measured change of the water volume
- $\Delta$ Ve is the equipment volume change due to a change of the walls temperature and the inside pressure
- $\Delta$ Vw is the variation of the water volume due to a change of its average temperature and pressure

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

$$L = \Delta Vr/Vo,w \qquad (2)$$

where Vo,w is the initial water volume.
A variation of the atmospheric pressure value also partecipates 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 can be written:

$$\Delta Ve = (\Delta T)e,\ aver.(\Delta V/\Delta T)e + \Delta Pw\ (\Delta V/\Delta P)e \qquad (3)$$

$$\Delta Vw = (\Delta T)w,\ aver.(\Delta V/\Delta T)w - (\Delta Pw+\Delta Patm)\ (\Delta V/\Delta P)w \qquad (4)$$

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
- $(\Delta V/\Delta T)e$ is the equipment volume variation due to a unitary change 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:

$$(\Delta P)w = \gamma w\ \Delta Hm \qquad (5)$$

being $\Delta$ Hm the measured change of the water free surface level and $\gamma$w the specific weight of water

- ($\Delta$patm) is the measured atmospheric pressure change.

The above relationships still held if another fluid, in addition to water, 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, modifying the relationship (4) as follows:

$$\Delta Vf = (\Delta T)f,aver.(\Delta V/\Delta T)f - (\Delta Pf+\Delta Patm)\ (\Delta V/\Delta P)f \qquad (4a)$$

where the symbol "w" has been substituted by "f", to account for a generic fluid medium.
The parameter ($\Delta$V/$\Delta$p)f being unknown "a priori", must be determined experimentally. So, during the main test one more test was conceived in order to achieve the overall comprimibility of the fluids contained by the component and estimate the volume of the contingent gaseous medium entrapped inside.
By introducing the relations (3), (4a) and (5) in the relation (1) and rearranging, the final relationship to be used to determine if a leakage occured during the test is obtained:

$$\Delta Vr = \Delta H_m Sp(1+ \frac{\gamma_w}{Sp}\frac{\Delta V}{\Delta p}) - \Delta Vf,t + \Delta Ve,t + \Delta Patm\ (\frac{\Delta V}{\Delta p})f \qquad (6)$$

or, in terms of leak rate L:

$$L = \Delta Vr/Vo,f \qquad (7)$$

where:

- Sp is the cross section area of the container above the piezometric tube
- ($\Delta$V/$\Delta$p) is the overall comprimibility of the system, equal to ($\Delta$V/$\Delta$p)f + ($\Delta$V/$\Delta$p)e
- $\Delta$Vf,t is the overall thermal expansion of the fluid medium, equal to $\Delta$Tf, aver. x ($\Delta$V/$\Delta$T)f
- $\Delta$Ve,t is the equipment thermal expansion, equal to $\Delta$Te, aver. x ($\Delta$V/$\Delta$T)e
- K is a correction factor, equal to (1 + ($\gamma$w/Sp) x ($\Delta$V/$\Delta$p)) which accounts for the effects of the overall comprimibility of the system
- Vo,f is the volume of the fluid initially contained inside the component.

Really: $V_{o,f} = V_{o,w} + V_{o,gas}$.
But, as $V_{o,gas}$ is anticipated to be smaller and smaller than $V_{o,w}$ (as it has been confirmed experimentally), it can be put: $V_{o,f} \cong V_{o,w}$

## 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 overall volume of the 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. Now it is sufficient to say that a volume of about 100 -:- 140 liter of air has been "measured" to be entrapped inside the component 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 (see, Figure 5) of the structure which unitary loads were imposed to.
The following values were obtained:
- Case (a) $(\Delta V/\Delta T)_e$ = 3.78 liter/°C

- Case (b) $(\Delta V/\Delta T)e = \pm 0.069$ liter/°C
- Case (c) $(\Delta V/\Delta T)e = \pm 0.034$ liter/°C

For cases (b) and (c) the sign "+" holds for temperature growing from inside to outside.

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 (see Figure 5)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, (Te, aver.).

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 (see, Figure 4). 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 expansion, $(\Delta Vw,t)$.
It has to be noted that no contribution of any gaseous media to the overall fluid thermal expansion was expected. So that the term $\Delta Vf,t$ of equation (6) is practically equal to $\Delta Vw,t$.

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 (see, Figure 4).

From their answers, using a weighted averaging technique, the average temperature of the water "Tw,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 Tw, aver.

F) Evaluation of the atmospheric pressure change, $(\Delta patm)$.

The atmospheric 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, $(\Delta Hm)$.

This amount was measured by means of manometers placed in correspondence of the bottom of the transparent container located above the piezometic 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 en 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 incrase is related to:
- the comprimibility of water itself, $(\Delta V/\Delta p)w$
- the deformability of the component under pressure, $(\Delta V/\Delta p)e$
- the comprimibility of any other fluids 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.
Hypothizing 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 write:

$$V = - p\ (\Delta V/\Delta P)air \qquad (8)$$

from which, once known ($\Delta V/\Delta p$)air 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 (see, Figure 6 and Tables 1(a) and 1(b)).

## 5. SOFTWARE DESCRIPTION

The various parameters were scanned and measured by means of 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 experimentally determined or calculated values introduced where necessary.
The volume of water has been divided in "n" elementary volumes Viw each associated to a temperature sensor $T_{iw}$. to determine the mean averaged temperature of the filling water to each elementary volume a ponderation coefficient, Ciw, defined as follows was associated:

$$Ciw = Viw/\sum_{1}^{m} i\ Viw \qquad (9)$$

The mean averaged temperature is then

$$Tav = \sum_{1}^{m} i\ Ciw\ Tiw \qquad (10)$$

The water volume change due to the mean average water temperature (Tav), has been determined by means of the Landesen formula:

$$\Delta Vw/Vo,w = \alpha\ Tav + \beta T^2av + \gamma T^3av + \delta T^4av \qquad (11)$$

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

$$\Delta V/V = AO + A1xH \qquad (12)$$

where H is the elapsed time expressed in decimal hours. The standard deviation $\delta r$ and the amount of data were at last 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 devices: resolution, precision or sensitivity, repetitiveness, stability. Other ones are subordinate to the

uncertainty on the 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 the water temperature

The error on resolution and precision of the 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 all these 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 ones. That is due the fact that the water temperature variation was measured by means of a reduced number of sensors: depending on this number the value which is obtained is more or less representative of the mean water temperature.
To assess this last one, to each 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 $Vw/Vo,w = f(Tw)$ be get by the data of only one sensor. So proceeding the parameter $Vw/Vo,w = f(Tw)$ over the last twenty four hours of measure was estimated to be in the range:

$$0.575 < \Delta Vw/Vo,w < 1.062 \text{ (l/day)}$$

with the following confidence interval:

$$0.326 < 2\delta r < 0.31 \text{ (l/day)}$$

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 was, for both the test:

$$0.326/\sqrt{14} = 0.08 \text{ l/day}$$

The same estimation made on the wall measured temperatures during the first test showed that the error on the equipment volume was negligible.

6.2 Measurement of the pressure

Due to the great sensitivity of the pressure transducers, the random error due to the electrical resolution was negligible.
The precision on the site calibration is generally of the order of 0.1%.So, an initial estimation 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 $\Delta$H 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):

$$e\ tot. = 0.02 + 0.01 + 0.03 + 0.08 = 0.14\ l/day$$

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) was 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 (see, Figure 6 and Tables 1(a) and 1(b)):

- 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 beginnning
  = 65.17 l/bar at the end.

The above values contain also the contribution of the deformability under pressure of the structure and the deformability under pressure of the water filling the Reactor Assembly.
Because these last amounts were already indipendently determined, being:
- $(\Delta V/\Delta p)e$ = 18,95 liter/bar ( from F.E. analysis)
- $(\Delta V/\Delta p)w$ = 3,50 liter/bar (from Tables)

the contribution of the structure and water together was estimated to be:

$(\Delta V/\Delta P)$ 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 entrapped 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 (see, Figures 9 and 10). Such a phenomenon is indicative of the presence of a gaseous medium because water has a so high thermal inertia that it can't follow rapid changes of temperature.

7.2 Determination of the inside trapped gaseous medium volume, (Vair)

Applying the equation (8) it is possible to estimate the volume of air present inside the component at the beginning and at the end of each leak test.
It was obtained:

- 1st leak test: at the beginning: Vair = 136 liter
  at the end: Vair = 124 liter

- 2nd leak test: at the beginning: Vair = 99 liter
  at the end: Vair = 90 liter

So, it has to be observed that during the test the volume of air decreased of:

$\Delta V = -12.0$ liter during the first leak test
$\Delta V = -9.0$ liter during the second leak test.

7.3 Leak Rate Evaluation

By means of the acquisition system before described an "apparent" leak rate was computed, obtaining (see, Figures 7 and 8 and Tables 2 and 3):

L global = - 2,93 liter/day for the first test
L global = - 2,75 liter/day for the second test

In Figures 7 and 8 the variation of all the significant parameters are diagrammed for the first and the second leakage test, respectively. In Table 2 the results of either of the leakage tests are summarized in terms of globale leakage rate, of leakage rate measured over the last 48 hours and over the last 24 hours.
In Table 3 all the parameters measured during both the tests are shown, together with the estimated error due to all the contribution before discussed.
It is interesting to observe that either of the global leakage rates measured during both the tests were greater than the specified allowable leakage rate (1.5 liter/day) and that in each of the two tests the following decrease of the fluid volume was measured:

- 1st Test: $\Delta V_{tot} = -10.5$ liter
- 1nd Test: $\Delta V_{tot} = -9.2$ liter

7.3 Interpretation of the results

If the decrease of the volume of the fluid contained in the Reactor Assembly determined during both the leakage tests is compared to the decrease of the volume of the air entrapped on the top of the Reactor Assembly, determined by means of the above described ( $\Delta V/\Delta p$) test, it is observed that these values are practically coincident.
So, the resultant leak rate could be considered really as an "apparent" one: no water leakage occurred during the test, but only a progressively decrease of the air volume.
The origins of such a decrease can be found in:

a) a likely leak of air through all the seals which were water tight but not air tight proved;
b) a progressively absorption of air by water.
This last possibility has been carefully examined. Applying three different approach, the following results were got:
1) Using the methodology of V.M. Ramm (5), an average absorption of 8.8 liter over 3 days was obtained.
2) Using the Fick law (4), an average absorption of 11.1 liter over 3 days was obtained.
3) Using the Henry law (4), an average absorption of 27 liter over 3 days was obtained.

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. To this decrease it was demonstrated the "apparent" leak rate measured was to be related. 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.

## ACKNOWLEDGMENTS

The tests herein described has been Organized by the Technical Staff of ANSALDO S.p.A. (test management) and ANSALDO COMPONENTI S.p.A. D. BREDA (test performance) under the supervision of ENEL (Italian Electrical Energy Agency) and ENEA-DISP (Italian Safety Authority).
To all the ANSALDO, ANSALDO COMPONENTI and BUREAU VERITAS people involved in these tests our thanks are devoted.
A particular acknowledgment has to be addressed to:
- Mr. F. CANIONI (BUREAU VERITAS)
- Mr. P. ANELLI (ANSALDO S.p.A.)

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# FIGURE 1a

View of the CIRENE Reactor Assembly

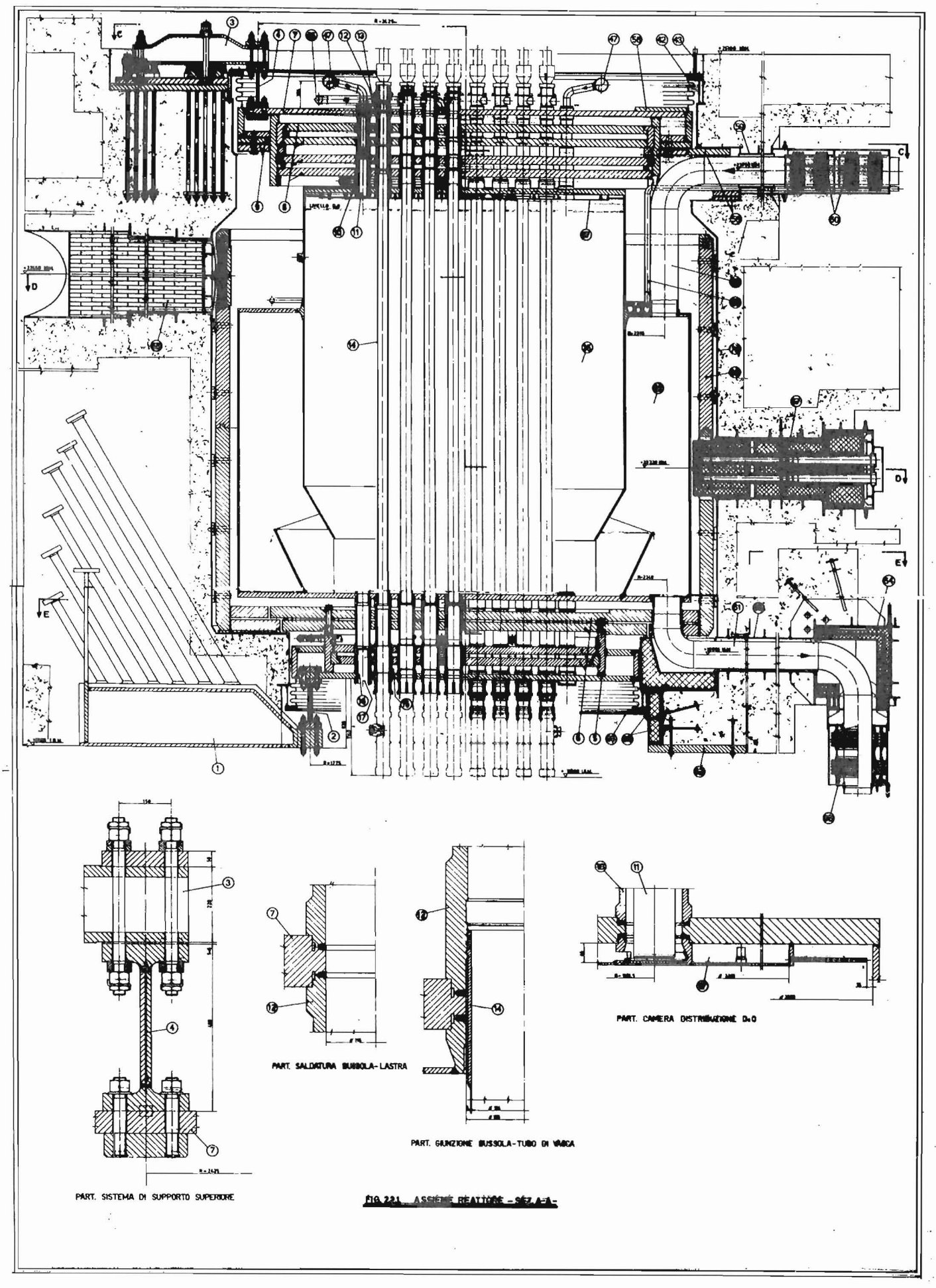
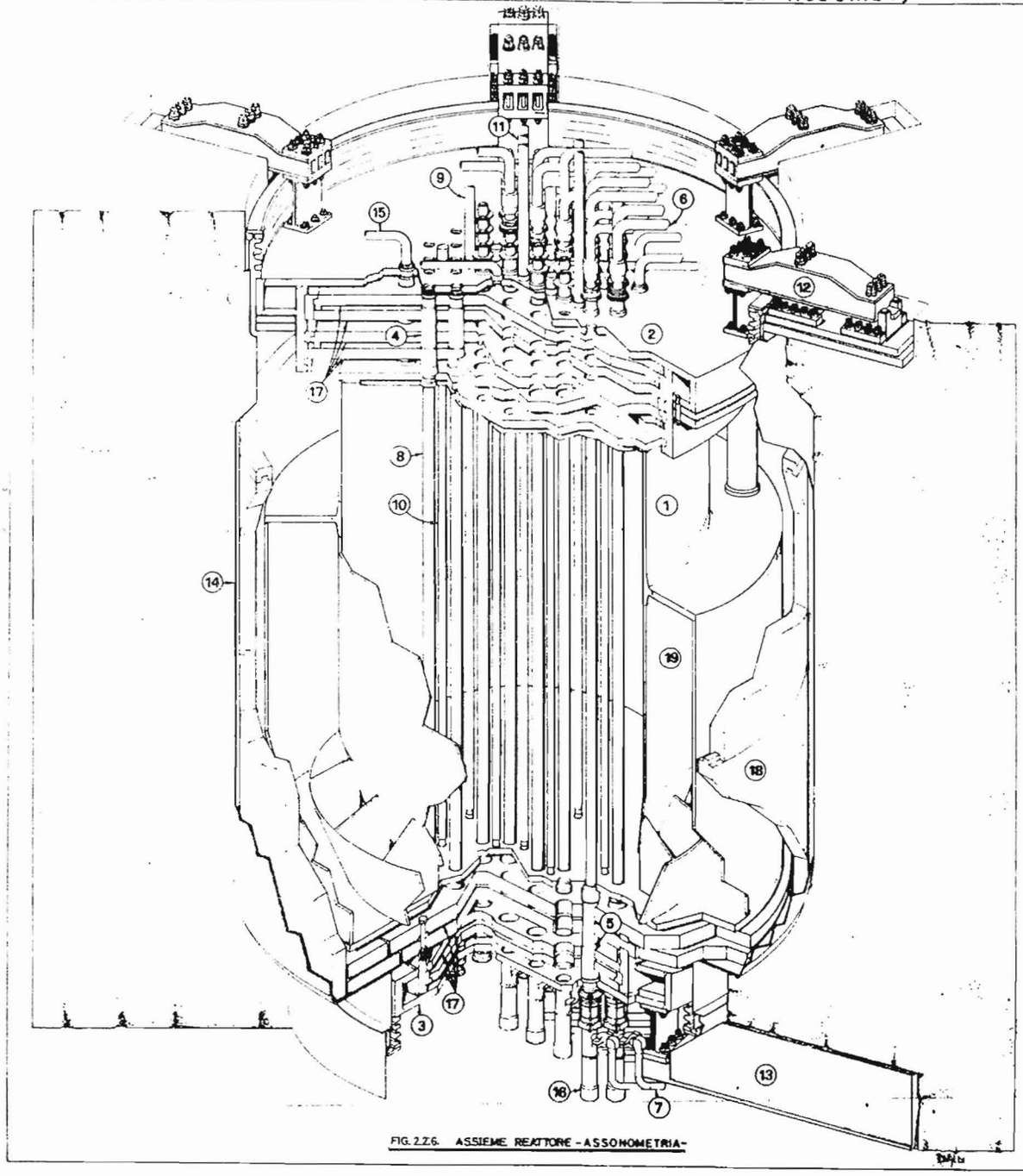



FIG. 2.2.1 ASSIEME REATTORE - SEZ. A-A -

## FIGURE 1b

View of the CIRENE Reactor Assembly



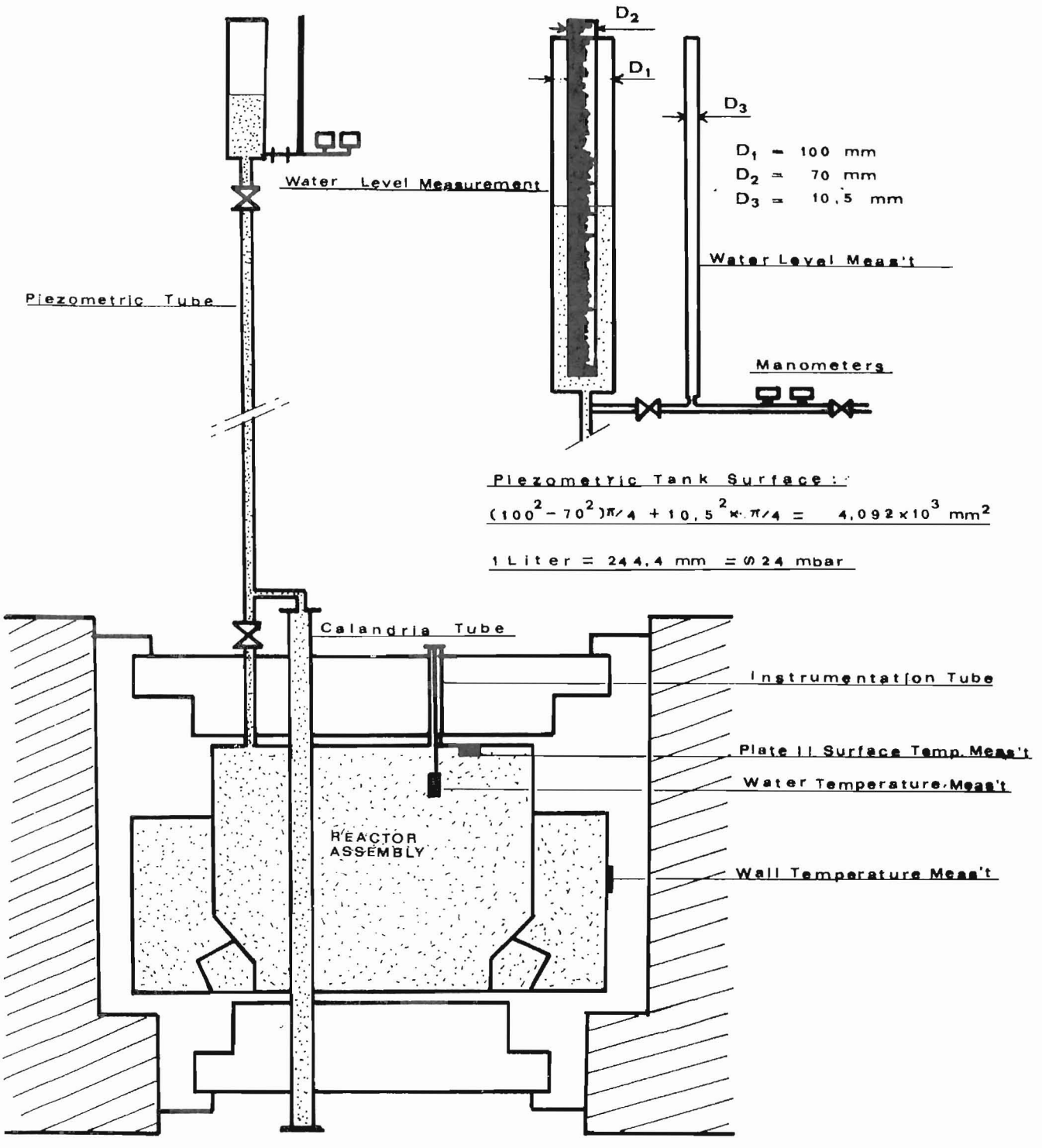
1 VASCA DELL' ACQUA PESANTE
2 LASTRA SUPERIORE CON ANELLO TORICO
3 LASTRA INFERIORE CON ANELLO TORICO
4 BUSSOLA SUPERIORE CANALE DI POTENZA
5 BUSSOLA INFERIORE CANALE DI POTENZA
6 TUBI USCITA FLUIDO TERMOVETTORE
7 TUBI INGRESSO FLUIDO TERMOVETTORE
8 TUBI DI VASCA
9 PROLUNGAMENTI BUSSOLA DELLE BARRE BIFASE
10 TUBI DELLE BARRE LIQUIDE DI ARRESTO RAPIDO
11 PROLUNGAMENTI BUSSOLA DEI SUPPORTI STRUMENTAZIONE IN NOCCIOLO
12 SISTEMA DI SUPPORTO SUPERIORE
13 SISTEMA DI SUPPORTO INFERIORE
14 RIVESTIMENTO METALLICO CAMERA REATTORE
15 TUBI INGRESSO $D_2O$
16 CANALE DI POTENZA
17 LASTRE SCHERMO ASSIALI
18 SCHERMI TERMICI LATERALI
19 RECIPIENTE DI SVUOTAMENTO

FIG. 2.2.6. ASSIEME REATTORE - ASSONOMETRIA -

FIG. 2.2.6

FIGURE 2

Simplified Sketch of the Basic Principle to Pressurize the Reactor Assembly and to Measure the Water Volume Change



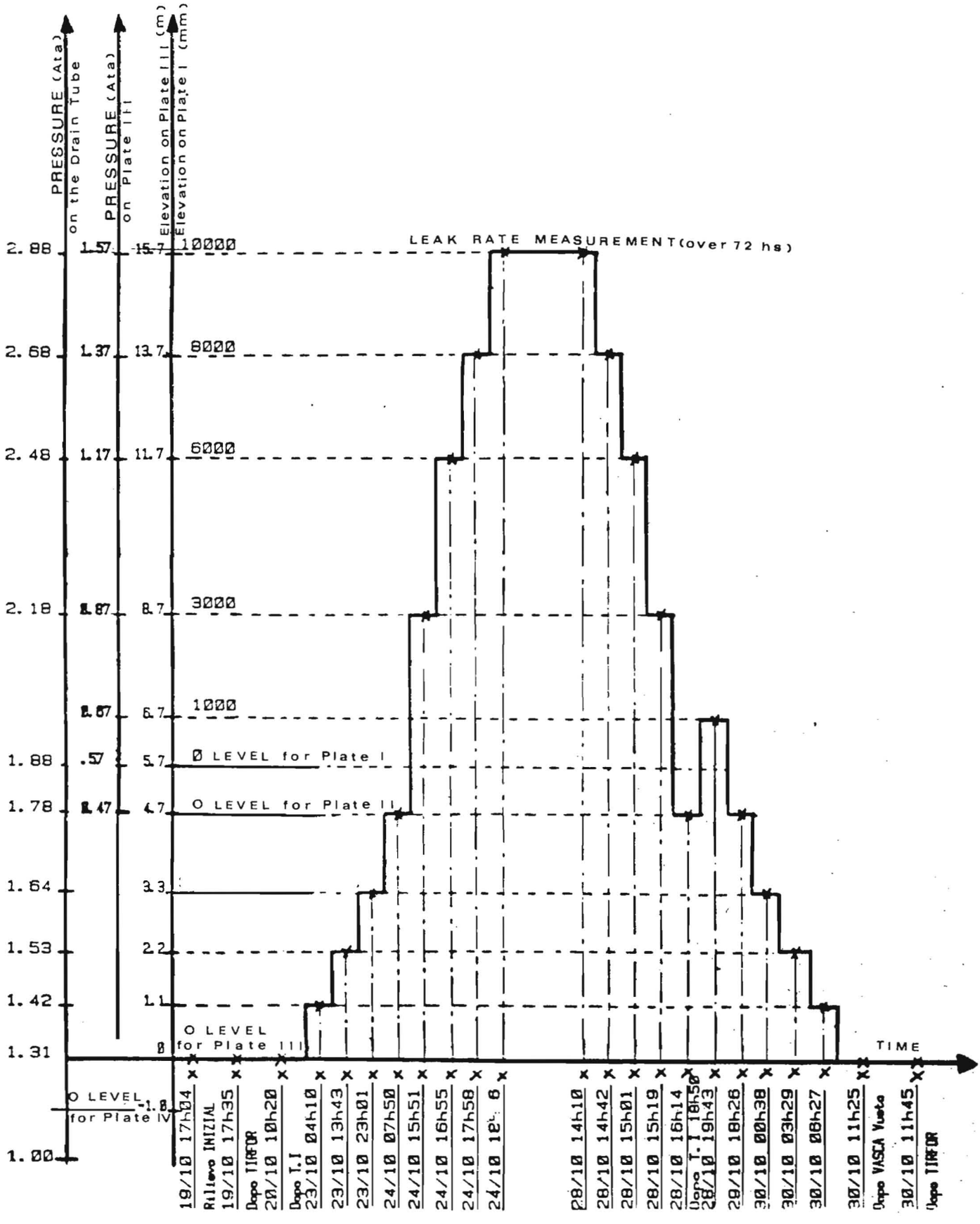
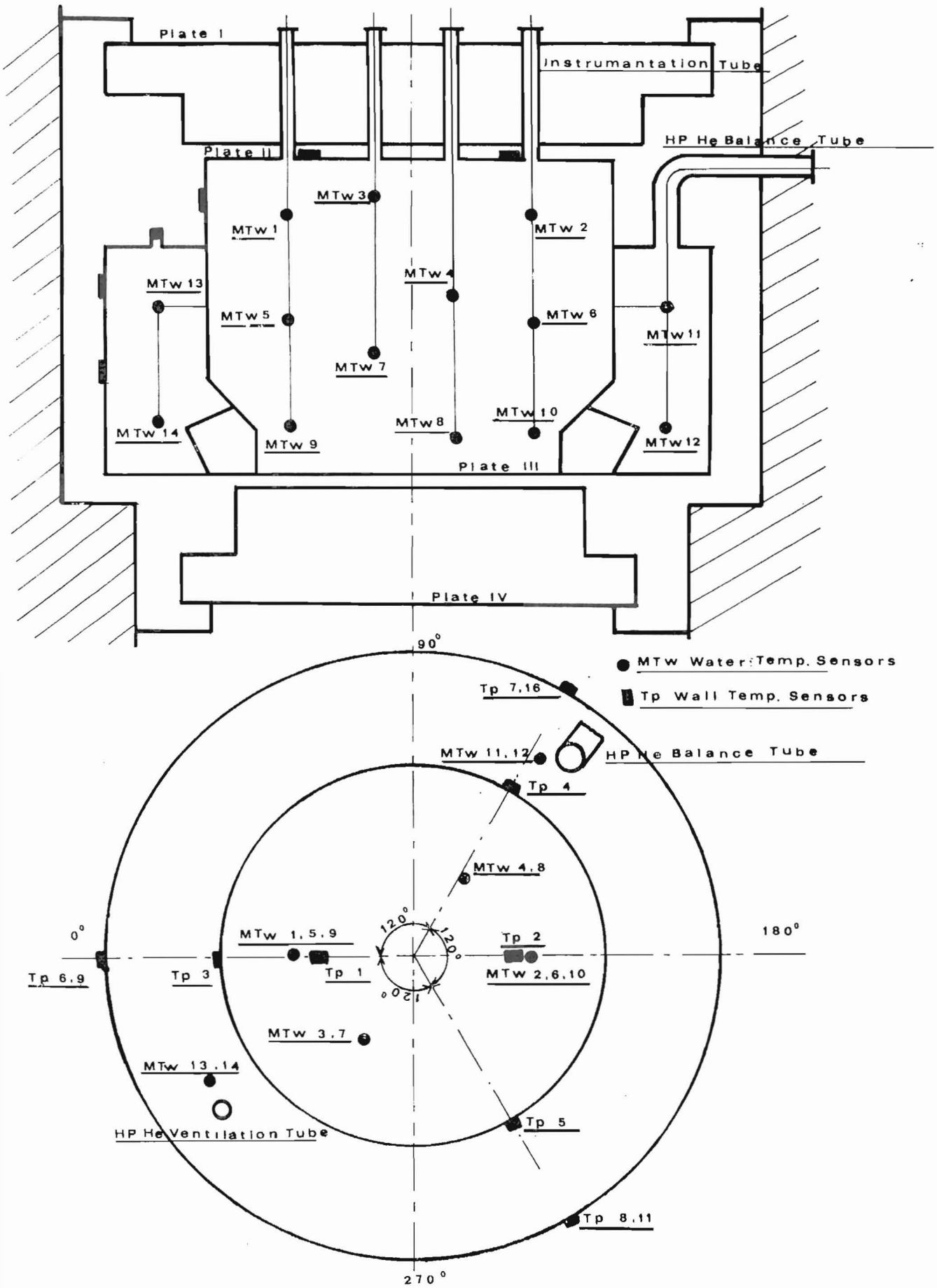



FIGURE 3

Pressurization Cycle for the Strength and Leakage Test

FIGURE 4

TEMPERATURE SENSORS LAY-OUT



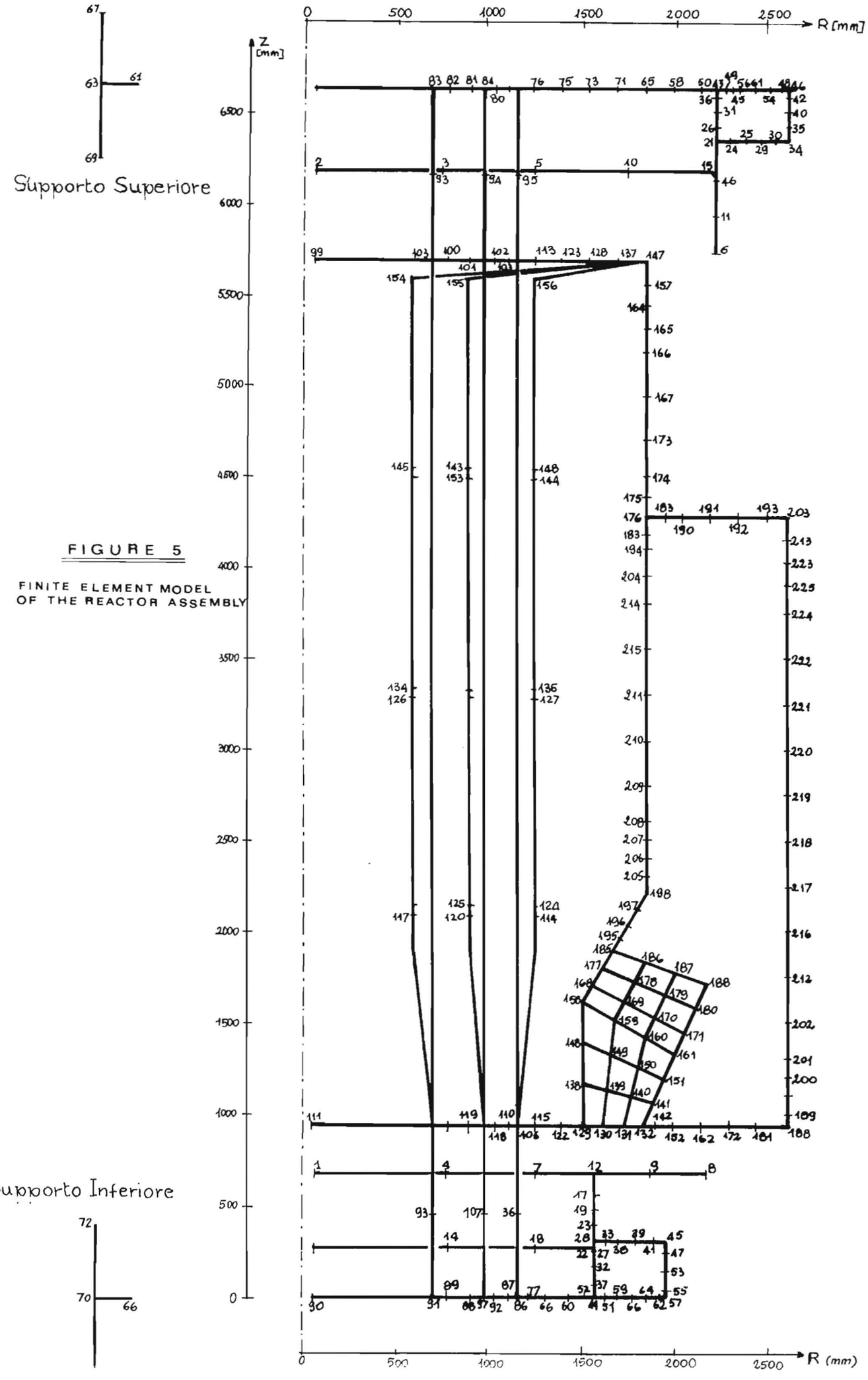



FIGURE 5

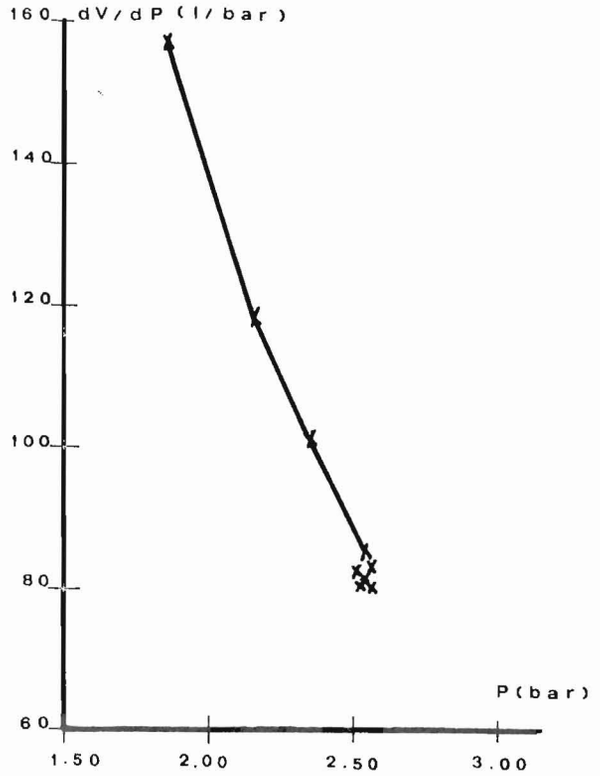
FINITE ELEMENT MODEL OF THE REACTOR ASSEMBLY

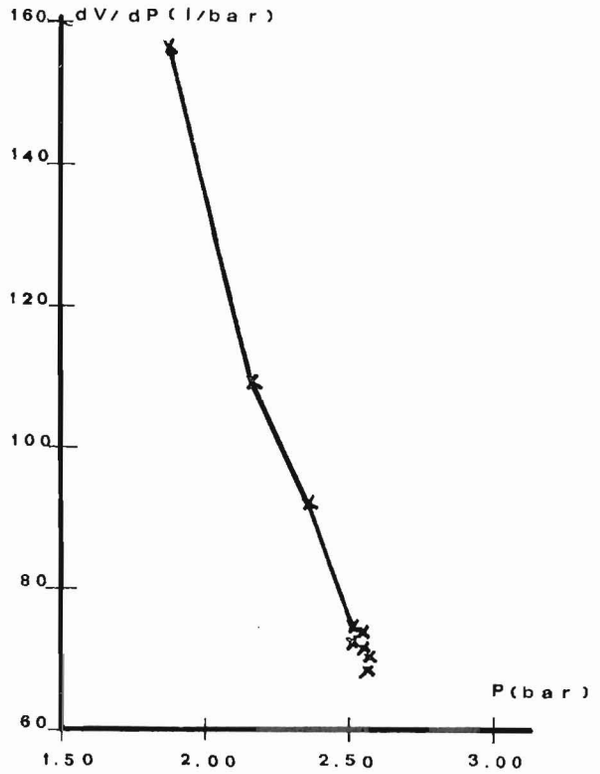
## FIGURE 6

Diagram of the ratio (dV/dP) as a function of pressure P

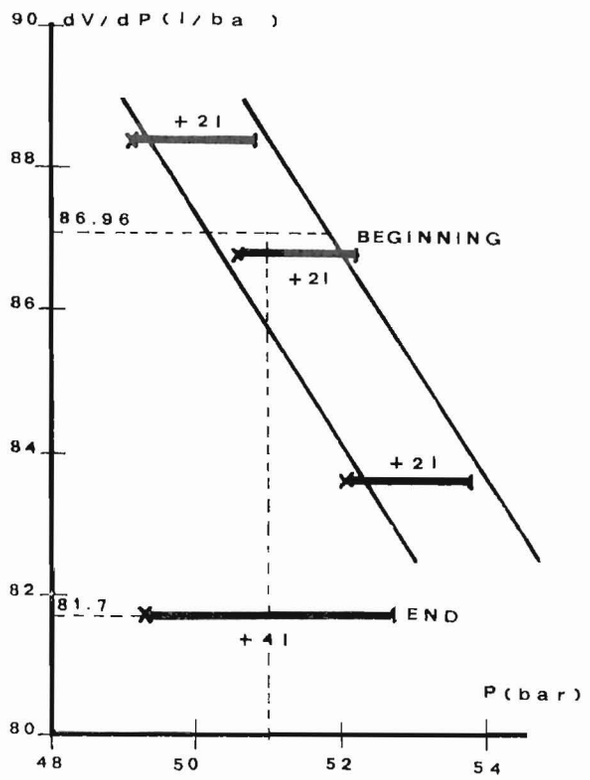
TEST 1 TEST 2

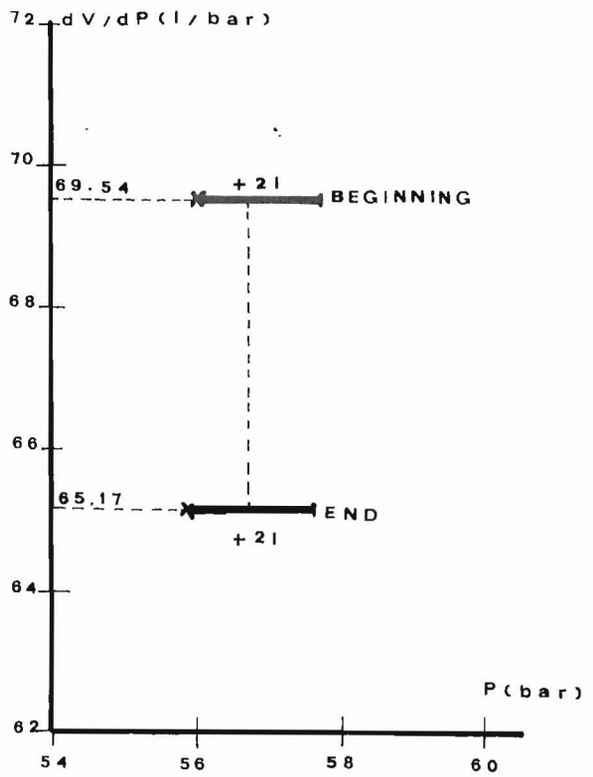
### WHILE PRESSURIZING




### AT THE BEGINNING AND AT THE END



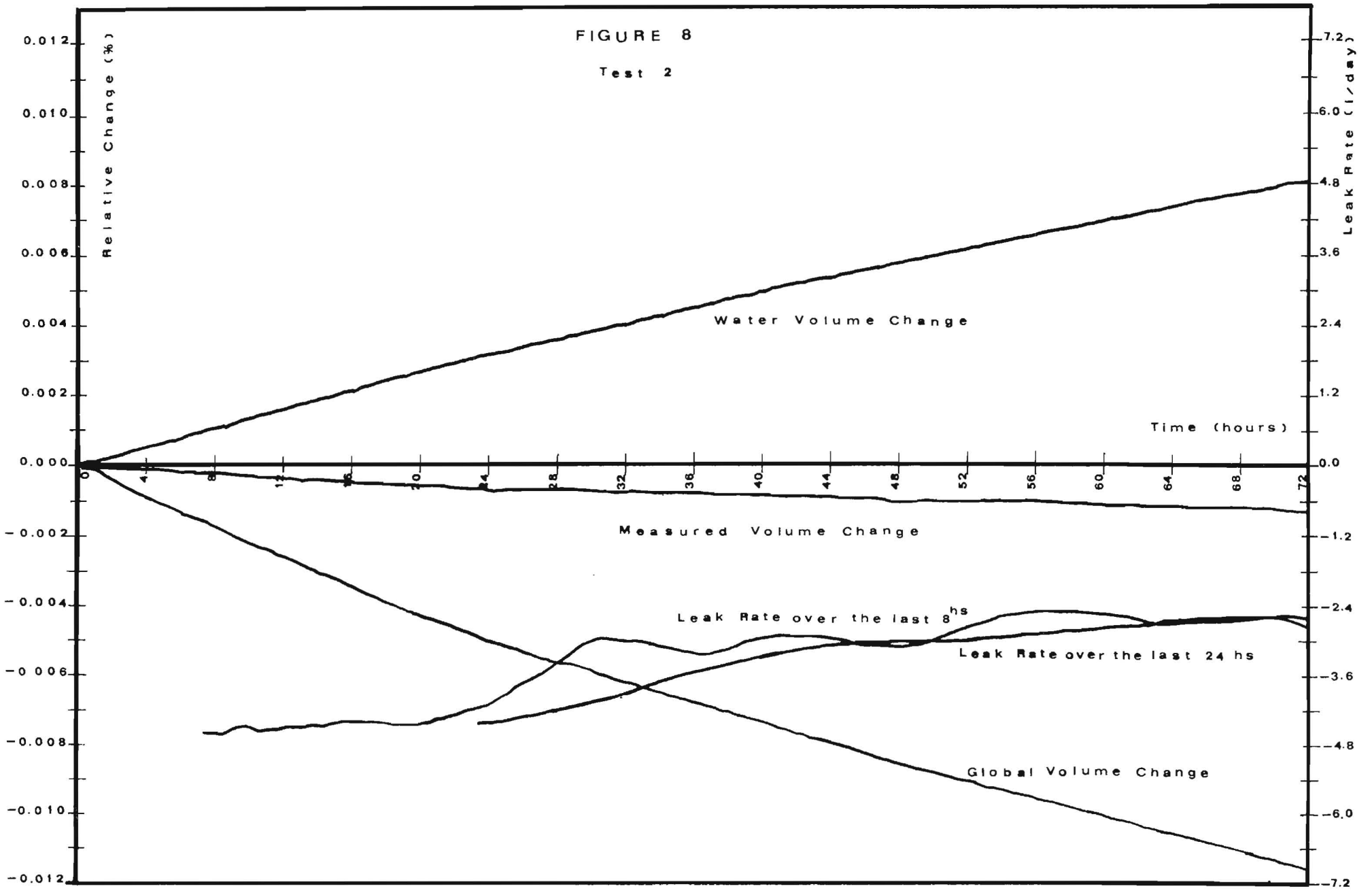


FIGURE 8
Test 2
Relative Change (%)
Leak Rate (l/day)
Time (hours)
Water Volume Change
Measured Volume Change
Leak Rate over the last 8 hs
Leak Rate over the last 24 hs
Global Volume Change
0.012
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
7.2
6.0
4.8
3.6
2.4
1.2
0.0
-1.2
-2.4
-3.6
-4.8
-6.0
-7.2
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72

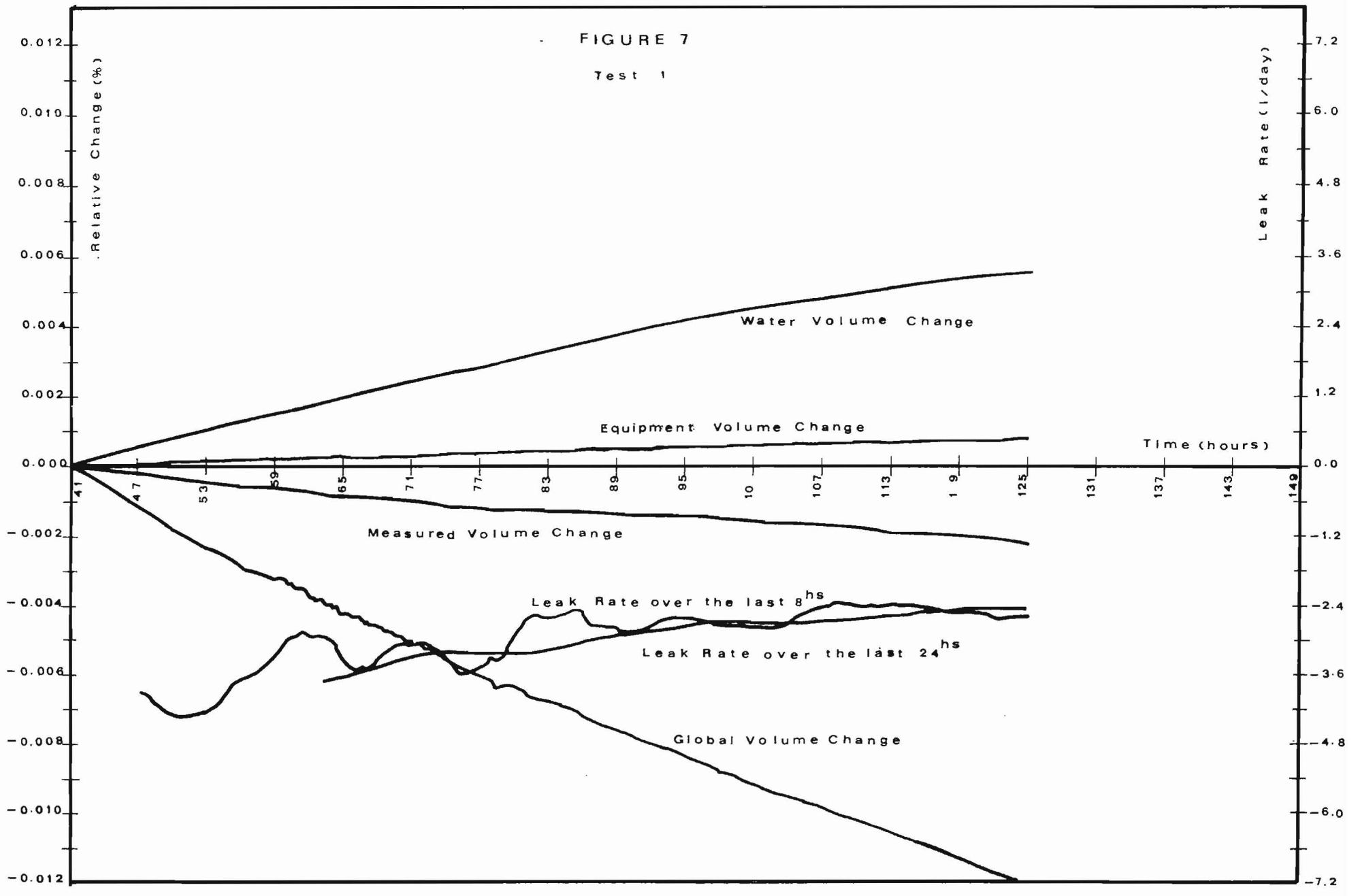


FIGURE 7
Test 1
Relative Change (%)
Leak Rate (l/day)
Time (hours)
Water Volume Change
Equipment Volume Change
Measured Volume Change
Leak Rate over the last 8 hs
Leak Rate over the last 24 hs
Global Volume Change
0.012
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
7.2
6.0
4.8
3.6
2.4
1.2
0.0
-1.2
-2.4
-3.6
-4.8
-6.0
-7.2
41
47
53
59
65
71
77
83
89
95
10
107
113
1 9
125
131
137
143
149

FIGURE 9

Walls and Plate II Surface Temperature Change during Test I

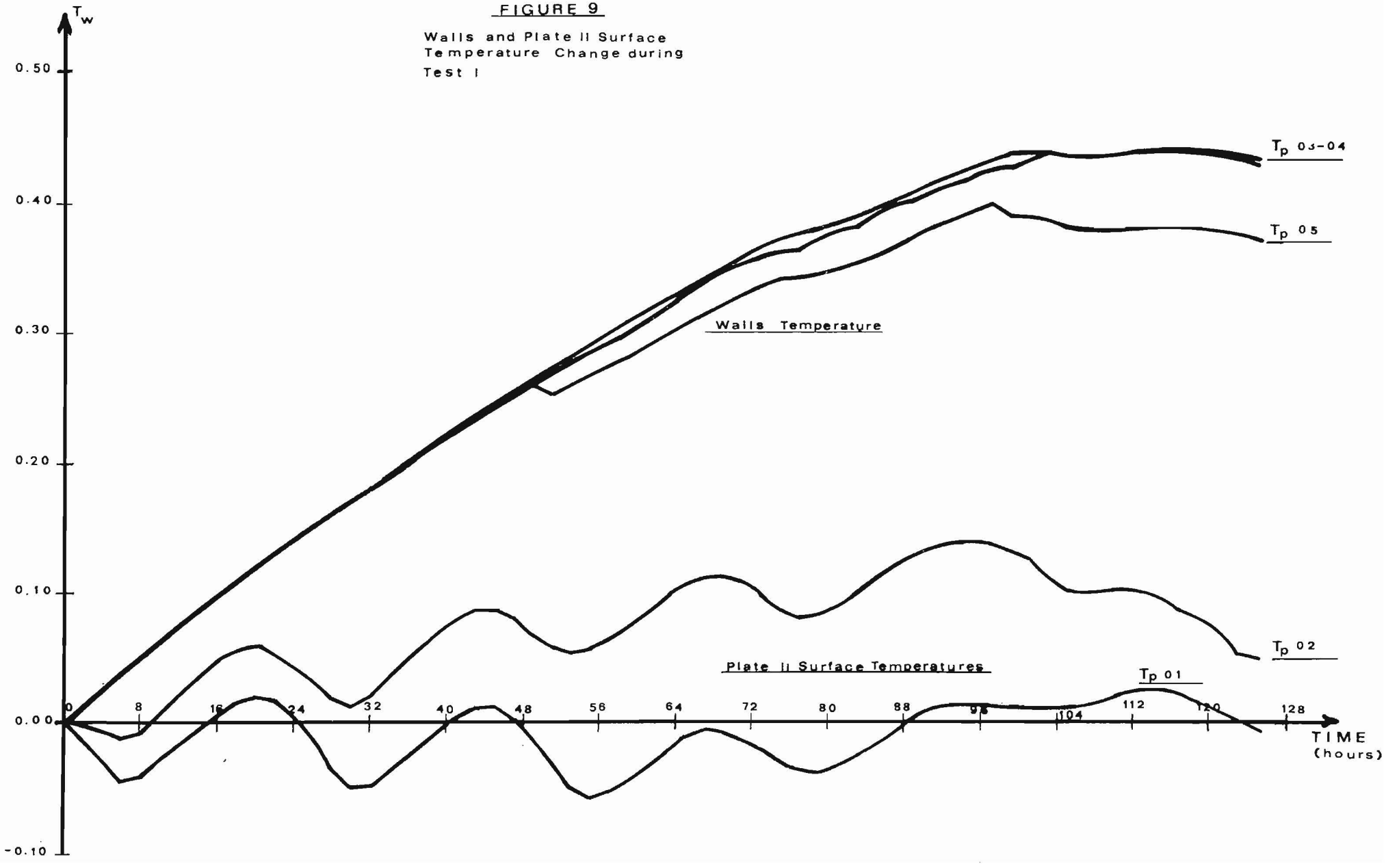


FIGURE 10

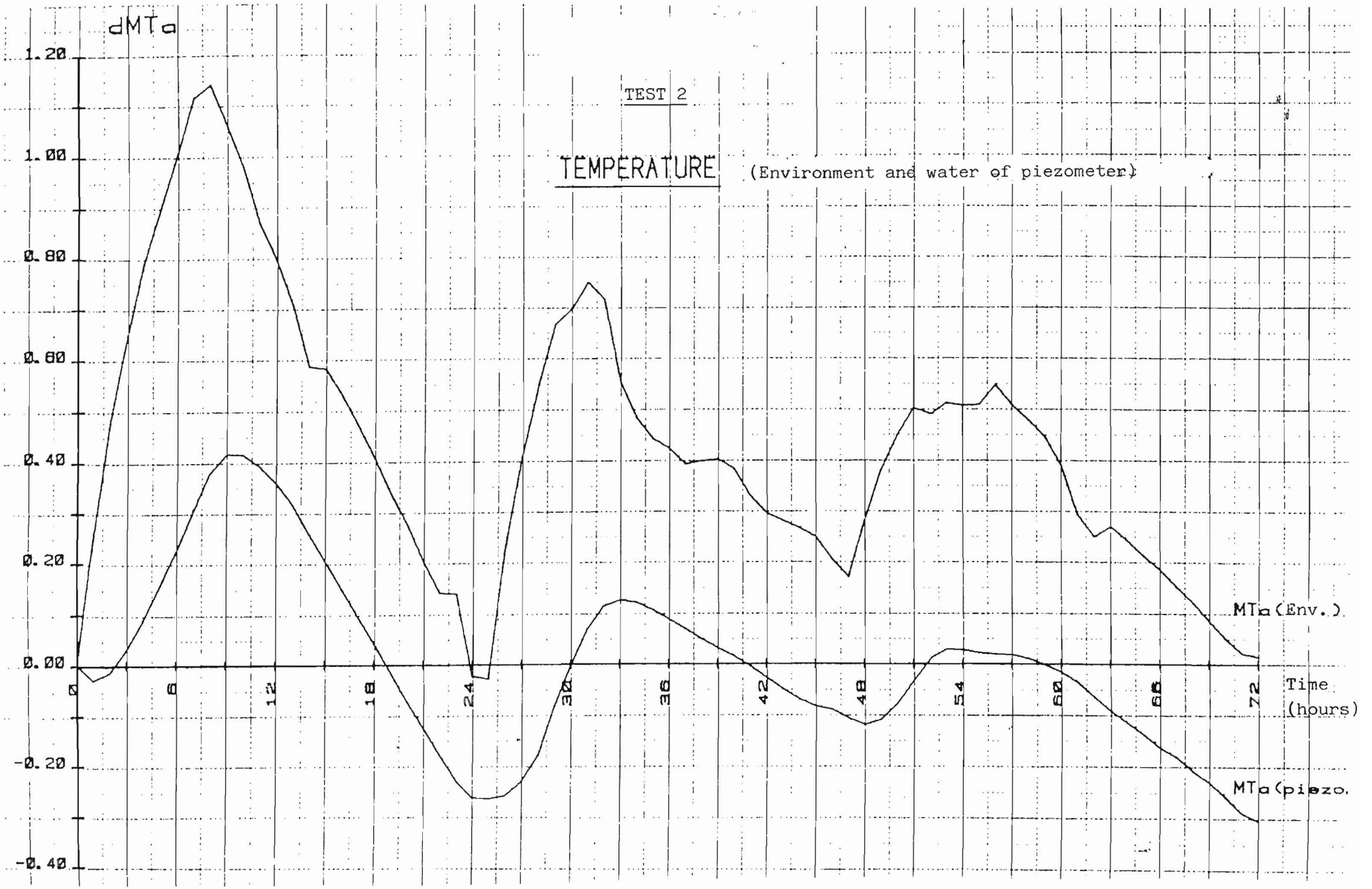

dMTa
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
TEST 2
TEMPERATURE (Environment and water of piezometer)
0
6
12
18
24
30
36
42
48
54
60
66
72
Time (hours)
MTa (Env.)
MTa (piezo.

TABLE 1a

Experimental evaluation of the ratio dV/dP

Test 1

| N° | Date | | Pressure on bottom of reactor assembly (bar) | Patm (bar) | Volume injected (liters) | ΔH theor (mm) | ΔH meas. (mm) | T water (°C) | dV Reactor Assembly (liters) | dP measure (bar) | dV/dP (l/bar) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.09 | 16h 20 | 1.861 | 1.010 | + 0.3 | 662.2 | + 19 | 25.6 | 0.291 | 1.86 | 156.8 |
| 2 | " | 18h 25 | 2.154 | 1.010 | + 0.3 | 662,2 | + 25 | 25,3 | 0.289 | 2.46 | 118.1 |
| 3 | " | 19h 20 | 2.350 | 1.010 | + 0.3 | 662.2 | + 29 | 25.7 | 0.287 | 2.64 | 101.2 |
| 4 | 9.09 | 20h 12 | 2.540 | 1.010 | + 2.0 | 488.7 | + 161 | 26.0 | 1.341 | 15.74 | 85.2 |
| 5 | " | 20h 37 | 2.558 | 1.010 | + 2.0 | 488.7 | + 162.5 | 26.0 | 1.335 | 15.89 | 84.0 |
| 6 | " | 20h 44 | 2.562 | 1.010 | + 2.0 | 488.7 | + 163.5 | 26.0 | 1.331 | 15.99 | 83.2 |
| 7 | 10.09 | 11h 00 | 2.526 | 1.008 | - 2.0 | 488.7 | - 167.6 | 26.0 | 1.314 | 16.33 | 80.5 |
| 8 | " | 12h 17 | 2.510 | 1.007 | - 4.0 | 977.5 | - 325.0 | 25.7 | 2.670 | 32.31 | 82.7 |
| 9 | " | 19h 37 | 2.532 | 1.006 | - 4.0 | 977.5 | - 331.0 | 25.9 | 2.646 | 32.41 | 81.7 |
| 10 | 11.09 | 01h 17 | 2.520 | 1.008 | + 2.0 | 488.7 | + 167.0 | 25.5 | 1.317 | 16.33 | 80.6 |
| 11 | " | 03h 40 | 2.557 | 1.008 | - 4.0 | 977.5 | - 335.0 | 25.9 | 2.629 | 32.76 | 80.3 |
| 12 | 12.09 | 20h 41 | 2.491 | 1.018 | + 2.0 | 488.7 | + 157.0 | 26.5 | 1.357 | 15.35 | 88.4 |
| 13 | " | 20h 59 | 2.506 | 1.018 | + 2.0 | 488.7 | + 159 | 26.5 | 1.349 | 15.35 | 86.8 |
| 14 | " | 21h 06 | 2.521 | 1.018 | + 2.0 | 488.7 | + 163 | 26.5 | 1.333 | 15.94 | 83.6 |
| 15 | " | 11h 34 | 2.493 | 1.008 | + 4.0 | 977.5 | + 331 | 25.6 | 2.645 | 32.37 | 81.7 |

TABLE 1b

Experimental evaluation of the ratio dV/dP

Test 2

| N° | Date | Pressure on bottom of reactor assembly (bar) | Patm (bar) | Volume injected (liters) | ΔH theor (mm) | ΔH meas. (mm) | T water (°C) | dV Reactor Assembly (liters) | dP measure (bar) | dV/dP (l/bar) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 24.10 15h 51 | 1.871 | 1.021 | + 0.3 | 662.2 | + 19 | 24 | 0.291 | 1.86 | 156.5 |
| 2 | " 16h 55 | 2.166 | 1.021 | + 0.3 | 662.2 | + 27 | 23 | 0.288 | 2.64 | 109.0 |
| 3 | " 17h 58 | 2.360 | 1.021 | + 0.3 | 662.2 | + 32 | 20.5 | 0.286 | 3.13 | 92.3 |
| 4 | " 18h 41 | 2.544 | 1.021 | + 4.0 | 977.5 | + 353 | 21.1 | 2.555 | 34.56 | 73.93 |
| 5 | " 19h 23 | 2.515 | 1.021 | + 2.0 | 488.7 | + 175 | 21.6 | 1.284 | 17.13 | 74.96 |
| 6 | " 19h 50 | 2.518 | 1.021 | + 2.0 | 488.7 | + 175 | 21.6 | 1.272 | 17.46 | 72.85 |
| 7 | 25.10 00h 15 | 2.546 | 1.022 | + 2.0 | 488.7 | + 180 | 21.9 | 1.263 | 17.62 | 71.68 |
| 8 | " 02h 07 | 2.560 | 1.022 | + 2.0 | 488.7 | + 185 | 21.8 | 1.243 | 18.11 | 68.64 |
| 9 | " 04h 00 | 2.562 | 1.021 | + 2.0 | 488.7 | + 182 | 21.8 | 1.255 | 17.82 | 70.43 |
| 10 | " 06h 00 | 2.560 | 1.021 | + 2.0 | 488.7 | + 183.5 | 21.7 | 1.249 | 17.96 | 69.54 |
| 11 | 28.10 13h 46 | 2.559 | 1.017 | + 2.0 | 488.7 | + 191 | 21.6 | 1.218 | 18.69 | 65.17 |

TABLE 2

Leakage test results

| Test | Relationship | L global | L 48 h (averaged) | L 24 h (averaged) |
|---|---|---|---|---|
| 1 | (1), | - 2.93 | - 2.60 | - 2.48 |
| 2 | (1). | - 2.75 | - 2.20 | - 2.19 |

Note: Relation (1) $\frac{dV_r}{V} = \frac{dV_m}{V} - \frac{1}{K}\left[\frac{dV_w}{V} - \frac{dV_e}{V} - dP_{atm}\left(\frac{dV}{dP}\right)fl\right]$

Where $K = \left(1 + \frac{\gamma_w}{Sp}\right)\frac{dV}{dP}$

TABLE 3

Volume changes during the leakage tests

| | | $dV_{mes.}$ | $dV_{(Ta)}$ | $dV_{T\ rec.}$ | $dV_{P\ atm.}$ | $dV/V$ |
|---|---|---|---|---|---|---|
| $F_{GLOBAL}$ | 1st Test | - 0.50 ± 0.01 (IC) | 1.41 ± 0.01 (IC) | 0.19 ± 0.002 (IC) | - 0.24 ± 0.01 (IC) | - 2.93 ± 0.03 (IC) |
| | 2nd Test | - 0.33 ± 0.01 (IC) | 2.32 ± 0.01 (IC) | (0.50) (± 0.002) (IC) | - 0.08 ± 0.01 (IC) | - 2.75 ± 0.05 (IC) |
| $F_{24h}$ | 1st Test | - 0.53 ± 0.02 (IC) | 0.93 ± 0.01 (IC) | 0.14 ± 0.002 (IC) | - 0.13 ± 0.03 (IC) | - 2.48 ± 0.02 (IC) |
| | 2nd Test | - 0.26 ± 0.01 (IC) | 2.01 ± 0.01 (IC) | 0.43 ± 0.002 | 0.04 ± 0.002 (IC) | - 2.19 ± 0.02 (IC) |