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ENS/ANS Topical Meeting on
NUCLEAR POWER REACTOR SAFETY
BRUSSELS - October 16-19, 1978

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LIQUID METAL FAST BREEDER REACTOR STEAM GENERATOR
SURVEY OF THE CONSEQUENCES OF LARGE SCALE SODIUM WATER REACTION

Introduction to the "RETONA" three-dimensional computing code

Summary :

The "RETONA" three-dimensional hydrodynamic computing code is being developed by ELECTRICITE DE FRANCE to survey the consequences, on the very plant, of a large scale sodium water reaction in liquid metal steam generators. In this communication, the heat-exchanger geometry is schematized and the problem solving process briefly described under assumed simplifying hypotheses. The application of the results to the CREUSOT-LOIRE steam generator selected for SUPER-PHENIX are given as an example.

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0. - INTRODUCTION

Large scale sodium-water reaction in steam generators is one of the particular safety problems in sodium cooled fast breeder nuclear power plants. In order to determine the results of such an accident on the plant, the assumption is made of a clean break of one of the bundle tubes, entailing :

- formation of a leak flow further to bundle decompression
- a sudden exothermic chemical reaction generating hot gas under pressure
- pressure variations which propagate and shake the plant structures.

With a view to assess the stresses on the tubes and steam generator walls, we propose to determine the speed and pressure fields in the sodium. Since cross wave propagation in hampered by the tube bundle and since structural reactions to hydraulic stresses are very fast, it is essential that a three-dimensional computing code be formulated.

In order to get a pessimistic but as actual as possible solution to the problem, a schematic diagram of the geometry is drawn and simplifying assumptions are made, allowing separation between the hydrodynamic survey and the other two physical phenomena. This is the purpose of the RETONA computing code, which solves the wave equation inside a three-dimensional enclosure representing hindrances to the propagation of waves generated by the chemical reaction.

The method of solution using the notion of "retarded potentials" and image theorem is summarized in this communication. Then, after a description of the schematic diagram of SUPER PHENIX steam generator, the results of a computation are given to show the RETONA code possibilities.

1. - ASSUMPTIONS AND CONSEQUENCES

1.1. - Leak flow-rate building up law

The clean breaking of a water tube brings about a leak flow that gradually tends to a critical value according to a building-up law which depends essentially on the way the water-steam tube is decompressed. In order that the leak flow-rate be a factor of the survey, the following simple formula is used :

$$Q = QC \times \frac{t}{TAU} \quad \text{with } t \leq TAU$$

$$Q = QC \quad \text{with } t > TAU$$

where QC = critical flowrate and TAU = time constant.

1.2. - Thermodynamic survey of the chemical reaction

The thermodynamic survey has shown that, at steam generator operating temperatures, water reacts with the sodium to produce soda. Namely :

$$\underset{l}{Na} + \underset{g}{H_2O} \rightarrow \underset{l,g}{Na\,OH} + \underset{g}{\tfrac{1}{2} H_2}$$

The enthalpic balance, applicable to constant pressure adiabatic transformations, shows that the soda is partly vaporized and, therefore, that the obtained products are at soda vaporizing temperature under the considered temperature.

The sodium is gradually put into motion by the gazeous chemical reaction products. It is assumed that the development of the open thermodynamic system formed by this gas mixture has the following characteristics :

- it remains concentrated in the shape of a single bubble that behaves like a perfect gas mixture
- during a dt elementary time, it is subject, in turn, to an instantaneous mixture between the old and the newly formed gas, with conservation of energy, and to a reversible adiabatic expansion.

That thermodynamic process gives a relation between the bubble pressure and volume variations, and it appears that the enthalpy of the gas mixture, referred to a water mole having reacted depends on the bubble expansion possibilities. Nevertheless , for the results given in this communication, we assume that the system temperature is constant and that the gas flow after the reaction is proportional to the water steam flow, a molar conversion factor can be defined as a link between those two quantities.

1.3. - Thermodynamic development of the argon volume

It is assumed that the argon volume behaves as a perfect single-atom gas subject to a reversible adiabatic transformation.

1.4. - Sodium hydraulic characteristics

The simplifying assumptions regarding sodium hydraulic characteristics are the following :

a) no swirl is created by the leak

b) the fluid is non-viscous

c) the liquid is but a little compressible : the product of the pressure into the compressibility factor $\alpha = \frac{1}{\rho c^2}$ is always very small in relation to 1

d) the sodium velocity is low in relation to sound velocity

e) the fluid transient motion is not influenced by gravitational pull.

Under those conditions, it is shown that the speed field is derived from a φ potential confirming the wave equation :

$$\Delta\varphi - \frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = 0$$

and complying with BERNOULLI's equation as follows :

$$-\frac{\partial\varphi}{\partial t} + \frac{V^2}{2} + \frac{P}{\rho} + gy = f(t)$$

2. - GEOMETRICAL SCHEMATIC DIAGRAM

2.1. - Steam generator description

A survey is made of SUPER PHENIX steam generator (fig. 1) the main characteristics of wich are the following :

a) The water tubes spiral wound in several layers between the external and internal cylindrical shells.

b) the water tubes are held up by braces dividing the sodium flow into quadrants over the full height of the bundle.

c) the sodium column is topped by argon gas.

2.2. - Geometrical schematic diagram

2.2.1. - Tube bundle

Since the leak is located in a quadrant bisecting plane it appears that for symmetrical reasons, the transient flow is not impeded when a tight wall is placed in the opposite quadrant (fig.1).

As seen from the top, the sodium flowing area looks as a circular ring ; after development, it becomes a trapeze likened with a rectangle the major side of which is equal to half the sum total of the circumferences of the two shells. (Fig. 2). Further to this evolution, the exchange area is shaped as a right-angled parallelopiped fully tight save for the top and bottom part : the two shells and the inserted solid wall split in two by the evolution are represented by the four sides.

The screens made of the water tube layers and their braces are schematized by permeable flat walls. So, the influence of the tube bundle is represented by a twin assembly of equidistant permeable walls parallel in the two cross ways.(Fig. 2). Each of the two series of walls is distinguished by a wave transmission factor which depends on the relative extent of the barriers and on the frequency.

2.2.2. - Top and bottom ends

The eight quadrants meet at tube bundle ends, so that, at the top and bottom part of the steam generator, two large hydraulic connections allow easy crossing of the pressure fluctuations from one to another quadrant.

Since computing time does not exceed a few tens of milliseconds the influence of systems external to the steam generator is neglected.

3. - DESCRIPTION OF THE RETONA COMPUTING CODE

3.1. - Solution principle [1] [2]

The wave equation (see § 1.4) within the steam generator space occupied by sodium is solved by the RETONA computing code. This is a boundary value problem ; in other words, the solution depends only on the field and potential values at border level. The plant schematic diagram shows that this sodium volume is delimited by (fig. 3) :

- the gas bubble resulting from the chemical raction, the border of which is altered and distorted with time
- fixed boundaries made of tight or permeable solid walls and a free surface.
- wide hydraulic connections at the two top and bottom ends of the plant.

3.2. - Dealing with the sodium-bubble border

Since the bubble dimensions are comparatively small in every direction, it appears that as regards the outside, namely the sodium, the following transformations :

- suppression of singularities on the sodium-bubble border
- bubble filling with sodium
- insertion of a multipolar sodium source

make it possible to replace the surface integral by a series of explicit wave functions.

3.3. - Dealing with fixed boundaries

From the schematic diagram it appears that, with the exception of the bubble, all the boundary conditions are found on fixed flat walls, parallel in the three directions. The image theorem makes it possible to replace the action of the latter by a treble series of regularly distributed multipolar sources, which are the images of the above mentioned object source.

3.4. - Dealing with the top and bottom cavities

The influence of the top and bottom hydraulic connections is dealt with approximately as follows :

- at that level, the wave condition depends only on the time and on the point height (Local single dimension model).
- the reflections are of tight wall type on the steam generator bottom end, and of combined type -tight wall and free surface combination- at the top end.
- the back waves to the tube bundle are evenly distributed over all quadrants.

3.5. - Time development law

The time variation of the potentiel is obtained by applying BERNOULLI 's equation :

$$-\frac{\partial\varphi}{\partial t}+\frac{P}{\rho}+\frac{V^2}{2}+gy=C^{te}$$

between the points on the sodium-bubble border and the top of the sodium head.

When the plant has a free sodium surface -as is the case with SUPER PHENIX- the top pressure is that wich prevails at time t in the argon volume. When the steam generator is under load, this pressure is obtained from the approached formula $\Delta p = \rho c \; \Delta V$ in which ΔV is the sodium speed that would be found at the top if this were not blind.

4. - APPLICATION TO SUPER PHENIX STEAM GENERATOR

As an example we give the results of an application to SUPER PHENIX steam generator. The calculation is mainly defined by the following parameters :

- a critical flow-rate QC = 20 kg/s and a time constant TAU = 10 ms (see § 1.1).
- a bubble gas temperature equals to 1660°K and a molar conversion factor of 74 % (see § 1.2).
- a leak level at 5 m from the bottom end of the steam generator.

Figures 5 and 6 show the pressure variations as function of height in three different subchannels of the leak quadrant at time 5 and 10 ms. The influence of the 17 layers of water tubes on the wave propagation is thus evidenced.

Figure 6 shows two pressures distributions at leak level in the two ultimate subchannels. The influence of the braces supporting the water tubes is now evidenced.

Figure 7 shows the pressure variations at different times along the straight line which intersects the damaged quadrant bissecting plane and the horizontal plane at leak level. The balancing speed of the pressure inside the quadrant is also evidenced.

5. - CONCLUSION

The survey of the hydrodynamic consequences of a large scale sodium-water reaction in sodium heated steam generators is possible with the use of the RETONA computing code. This is a three-dimensional code by which the wave equation is solved according to the singularities method combined with the image theorem. It is matched to a geometry that can be compared to a juxtaposition of right-angle parallelopiped interconnected by permeable walls in two orthogonal directions.

As an example the results of an application to SUPER PHENIX steam generator are given It appears that, at the very beginning, pressures are much higher wihtin the leak quadrant and sub-channel area. The mask effect due to the many water tube layers and the division of the plant into sections on the sodium side, is thus evidenced.

WORKS OF REFERENCE

[1] J.D. JACKSON - Classical Electrodynamics - John Wiley and sons. Inc 1967

[2] I. STAKGOLD - Boundary Value Problems of mathematical Physics - Volume II, The Macmillan Company 1968.

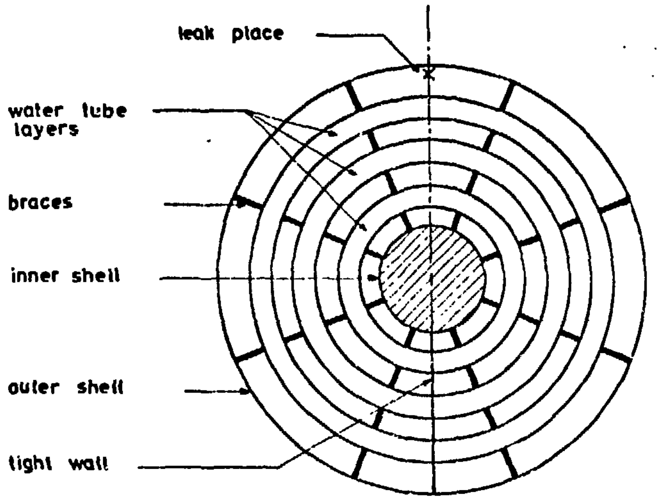

Figure 1. Cross section of the steam generator

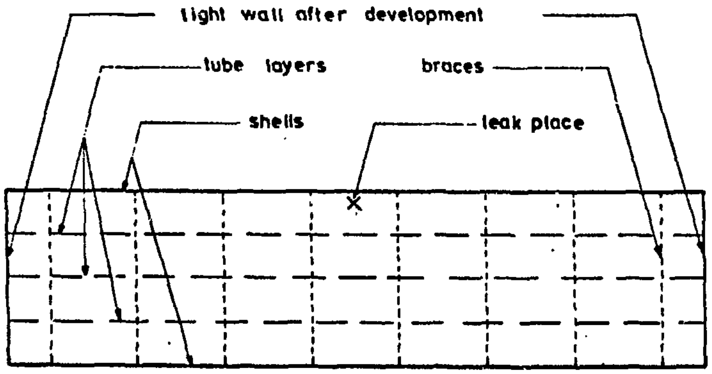

Figure 2. Schematic geometry of a cross section

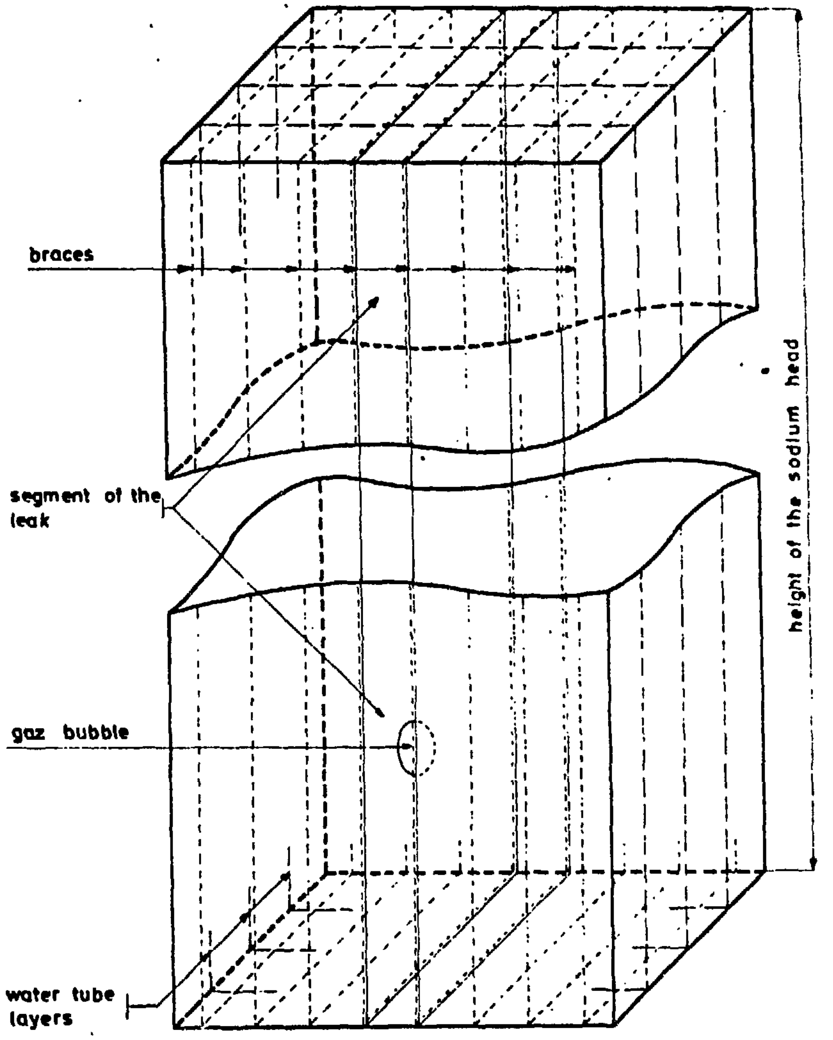

Figure 3. Schematic geometry of the steam generator

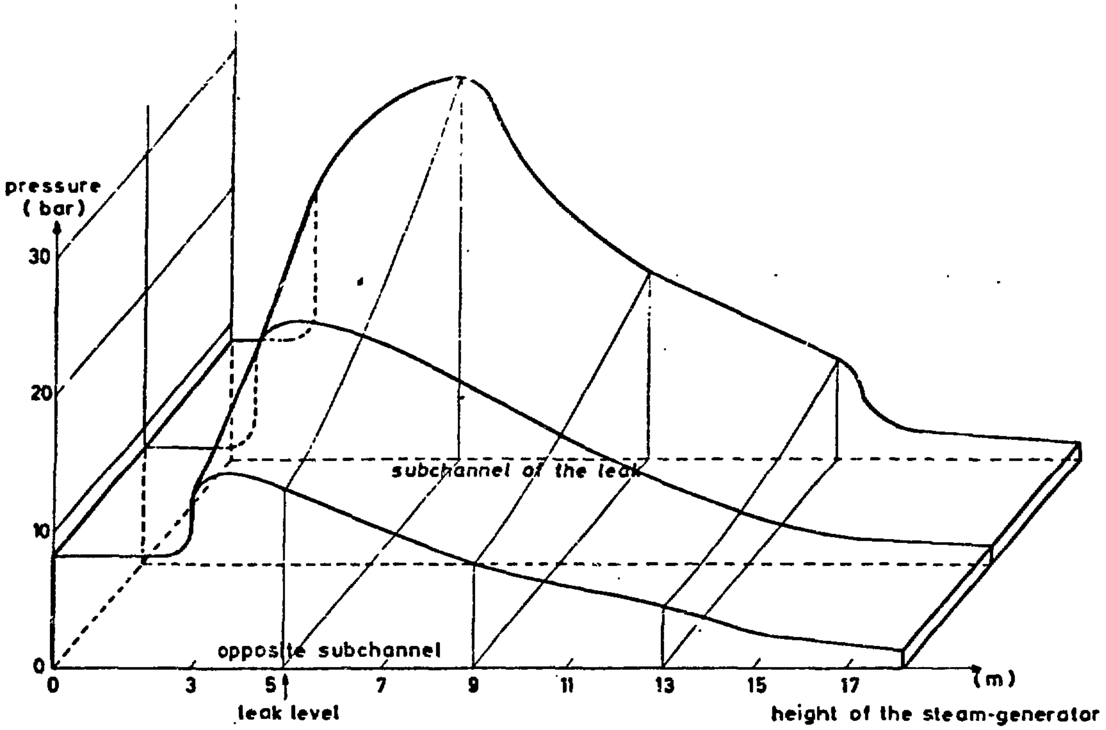

Figure 4 - Pressures inside a longitudinal section of the leak quadrant at time t=5ms

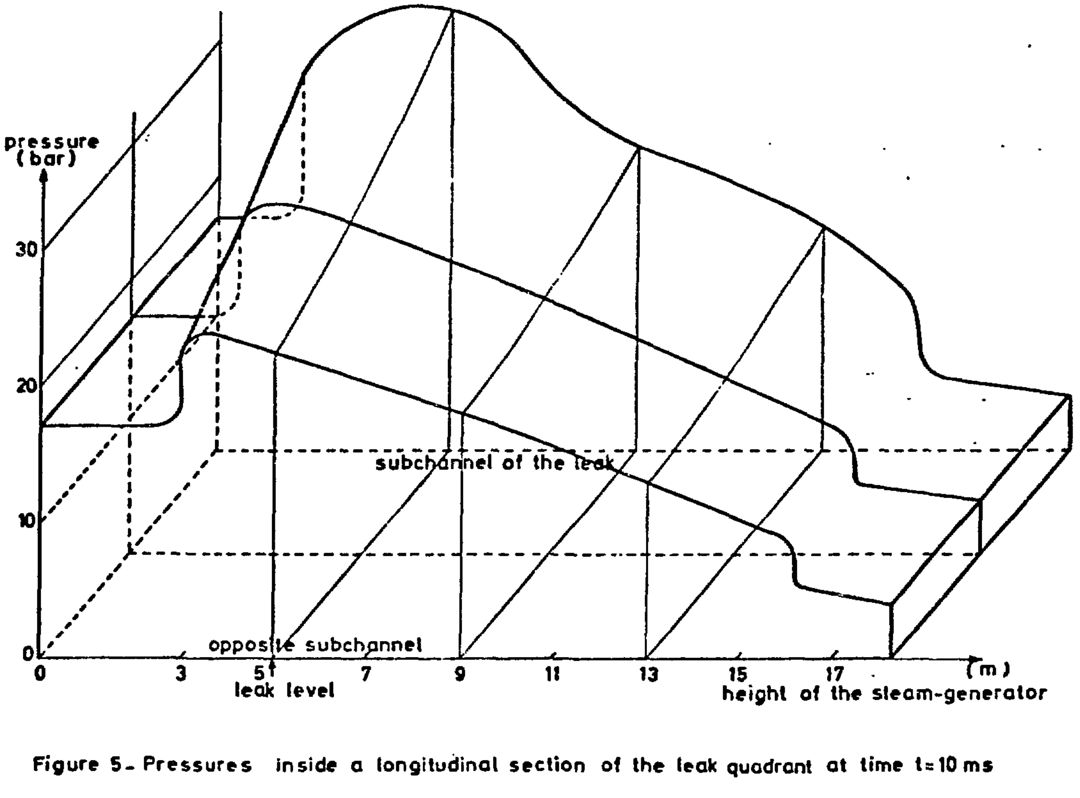

Figure 5 - Pressures inside a longitudinal section of the leak quadrant at time t=10 ms

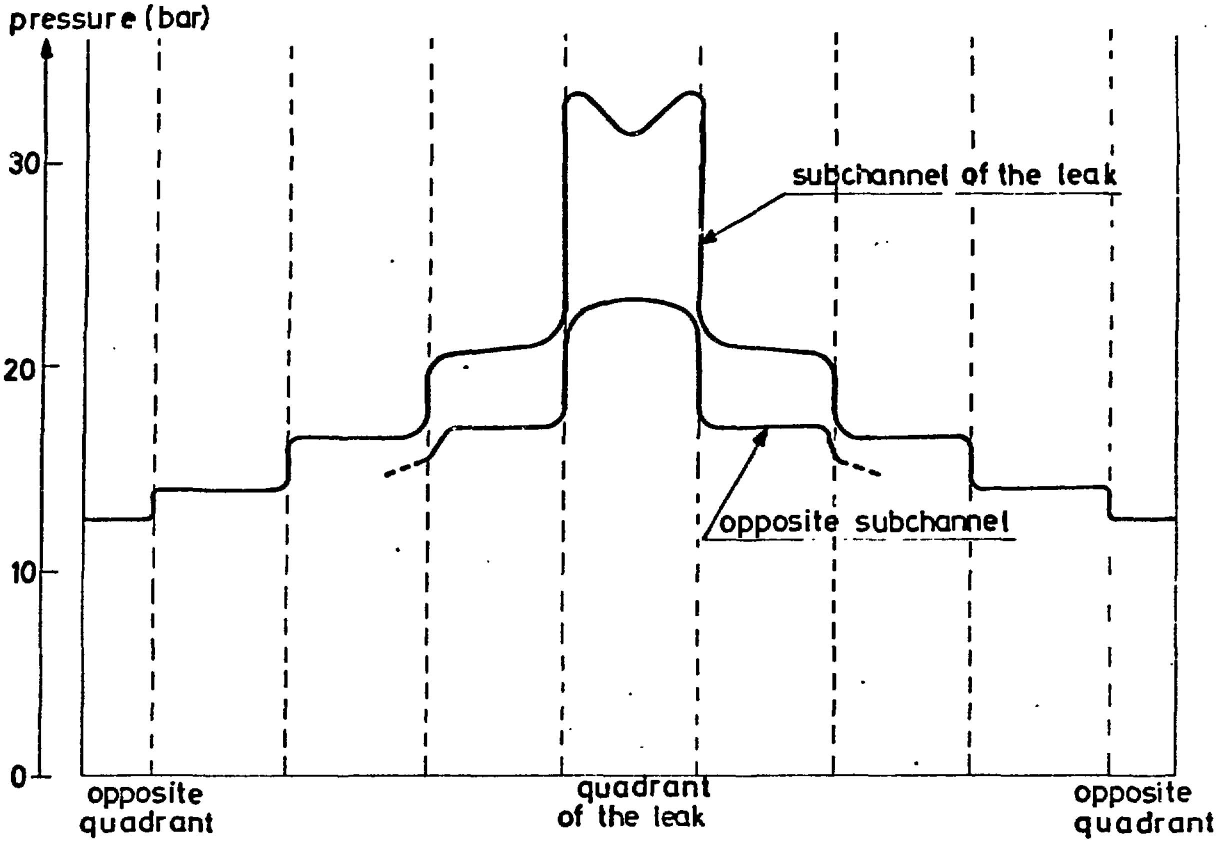

Figure 6_Pressures at the level of the leak (t= 10ms)

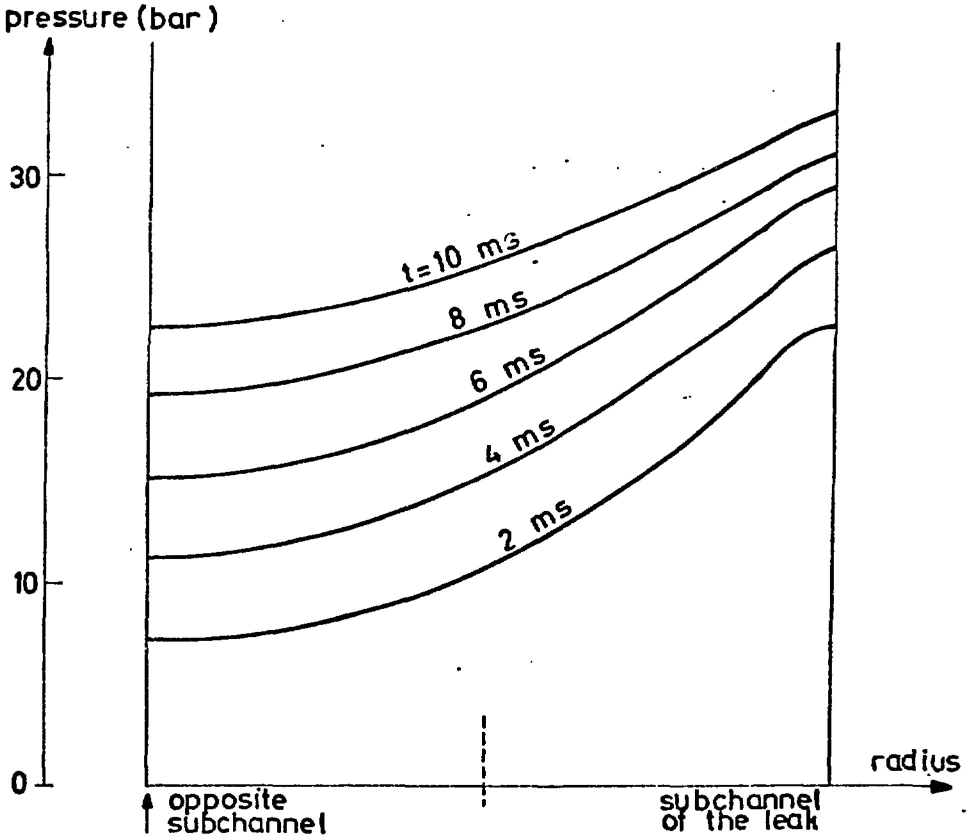

Figure 7_Pressures accross the tube layers at the leak level