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HFR REPORT No. 100: FAST LEAK IN CHANNEL H9

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1. PURPOSE OF RESEARCH

A fast leak in channel H9 is of special interest because the large volume experimental equipment is connected to the channel itself without a permanent material barrier. In addition, this containment is kept at a secondary vacuum, which accelerates any phenomenon of leakage compared to a channel kept at 2 bars of helium.

The purpose of the present study is to analyze the events that follow the failure of the channel in case of a fast leak. Given the complexity of the phenomena involved, the various times given in what follows should be considered as indications, with the overall purpose of the study being to define the various phases and their consequences for the reactor.

2. REVIEW

2.1. Placement of Channel H9 in the Building

Figure 1 shows a simplified schematic drawing of the reactor with channel H9. The reflector can, filled with heavy water and containing the fuel element, is submersed in a pool of light water, itself limited at the exterior by walls with a central concrete core, lined with stainless steel. The can has extrusions connected to collars that assure containment of the heavy water with respect to the pool and to the experimental areas in the reactor building. The channels penetrate the reflector can via the collars, with the heavy water being contained between the collar and the channel.

The channel is equipped with a housing that has a safety valve that connects the channel with the source changer containment. The isolation valve V16 mounted on a lateral pipe of the containment allows the volume to be delimited. This volume extends into the channel approximately 1 m^3.

The heavy water cooling the fuel element circulated in pipes across the bottom of the pool. The arrival line is connected to the central stack, closed at the top by the reactor valve; the departure line is connected to the suction basked placed on top of the reflector can. The siphon-breaking valve (CS) connects the arrival line to the crosshead of the departure line. The three natural convection shutters CN1, CN2 and CN3, open in case the pumps stop, allowing evacuation of the residual power of the fuel element by natural convection.

A portion of the heavy water flow that handles cooling of the control rod circulates through pipes that are connected to the tail of the reflector can. Since the natural convection shutter (CB) allows cooling by natural convection, the control rod is connected to the Reactor Coolant Shutdown Rod (CRAB) departure line downstream from the crosshead.

2. COOLING CIRCUITS

Figure 2 gives a basic schematic drawing of the primary D_2O circuits. The main pumps, whose shaft has a flywheel, discharge the heavy water through the principal exchangers placed in parallel in the central stack of the reflecting can. The water that has traversed the channels between the plates of the fuel element slowly rises into the reflecting can up to the suction basket. The portion of the flow taken into the fuel element for cooling of the control rod passes through the circuit called CRAB (Shutdown Rod, Cooling Circuit) toward the "shutdown rod" pumps that discharge through the shutdown rod exchanger in the arrival line of the principal circuit.

The natural convection shutters CN and CB, as well as the siphon breaker shutter CS, are closed by the action of the shutdown rod pumps. They are kept closed either by the high pressure in the arrival line in the principal circuit (CN and CS) or by the pressure in the Reactor Coolant Shutdown Rod (CRAB) departure line (CB).

The pressurization pumps discharging in the departure line of the main circuit give the water a pressure of 4 bars absolute in the center plane of the core.

After shutdown of the reactor and of the main pumps, the evacuation of the power is assured by the shutdown rod pumps alone, by opening of the check valve which connects the main circuit with the CRAB circuit.

3. Loss of Seal

3.1. Failure Mode and Calculation Hypothesis

Let us consider the failure of channel H5 under the following conditions:

-- the reactor is operating normally,

-- The pressure of the heavy water around channel H9 is kept at 4 bars absolute, the safety valve is open, The isolation valve V16 is closed, the source changer containment and the channel are at secondary vacuum.

The failure suddenly opens up the entire cross section of the front part of the channel at the point of connection between the cylindrical ferrule and the thin bottom. The heavy water enters the channel in the form of a piston accelerated by the pressure differential between the inside and the outside.

Calculations have been made to trace the sequence of these events. The following hypotheses have been chosen:

-- The entrance orifice has a cross section with a diameter of 200 mm,

-- the source changer cart is not in the channel,

-- the walls along the path of the water in the channel are smooth,

-- the heavy water is a perfect liquid with a constant density and without viscosity,

-- there are no effects of inertia when the water is moved or speeded up,

-- there is no shrinking effect of the spray at the point of the entrance orifice.

-- the pressurization pump flow rate is so low (approx. 7 l/s) that their role can be neglected in the case very rapid phenomena exist.

Given the exclusion of any phenomena of friction, the results of calculation are relative to an unfavorable case in which the phenomena take place faster than they actually do in reality.

The equations that allowed the problem to be calculated are given in Appendix A. The results are presented in the form of tables AI and AII which give the pressure in the reflector can at the level of the axis of H9 (p_a), the pressure (p_i) in the source changer containment, the flow rate (v) at the entrance orifice, the volume of water ΔV entering the channel during the time lapse Δt, and the volume V that entered the channel since the failure.

3.2. Sequence of Events

The events taking place during the loss of seal are given in the form of chronology based on tables AI and AII.

t_0 = 0 Loss of seal. Cross section at point of entry orifice: 0.031 m^2.

The water that enters the containment kept at secondary vacuum partially evaporates, which causes the pressure in the containment to rise very quickly to the relative saturation pressure at 50° C: p_i = 0.112 bar [1]. The volume of liquid water required to fill the 1 m^3 containment with the steam is 0.121 l.

Flow velocity: 26.6 m/s

Instant Flow rate: 836 l/s.

As the water enters the channel, the static pressure in the reflecting can drops at the rate of 1 bar/12.5 l [2]. The entry velocity decreases gradually.

t_1=10 ms Pressure in the reflector can: 3.4 bars

Rod drop order.

Main pump shutdown order

Volume of water that has entered channel: 7.7 l

Instant flow rate: 756 l/s

Entry velocity: 24.4 m/s

The flywheels mounted on the shafts of the main pumps assure a slow decrease of the flow rate after the pump shutdown order. Figure 4 shows the flow rate decrease as a function of time. After 4 seconds, the flow rate is still equal to 70% of the nominal rate; after 40 seconds, it is still equal to about 20%.

t_2=36 ms Pressure in the reflecting can: 2 bars

Entry velocity: 18.7 m/s

Instant flow rate: 580 l/s

Volume of water that has entered channel: 24.7 l.

Order to stop shutdown rod pumps.

The flow rate of the main pumps is practically unchanged.

t_3=80 ms Pressure in reflector can: 0.58 bars.

Entry velocity = 9.2 m/s.

Instant flow rate: 289 l/s.

Volume of water that has entered channel: 43.8 l.

Beginning of cavitation in the top point of the crosshead of the departure line of the main circuit (see Appendix A).

The flow rate of the main pumps is practically unchanged.

The first particles of water that entered at $t_0 = 0$ at a velocity of 26.6 m/s have covered a distance of approximately 2.1 m.

$t_3 = 80$ ms marks the end of the first phase of flow that is characterized by a pressure drop in the reflector can and a gradual decrease in the flow rate of the leak water (26.6 m/s to 9.2 m/s).

The second phase that follows is characterized by stable flow conditions at the entrance orifice. In fact, the cavitation taking place at the high point of the crosshead with maintenance of saturation pressure at this point determines the pressure level in the main circuit.

The leakage water from the reflector can that reenters the channel at a rate of 289 l/s leads to the formation of a volume of vapor starting with the high point of the crosshead which increases to the same extent. Since the flow rate of heavy water is assured under near nominal conditions (Fig. 4), the vapor bubble forming in the crosshead is carried by the water current into the vertical portion (Fig. 3) of the departure line. Because of the increasing hydrostatic pressure during the descent, the vapor recondenses gradually as it drops, provoking the formation of vapor in the crosshead as a compensation. These phenomena of evaporation and recondensation are taking place in a water current descending at 5 m/s leading to establishment of a two phase flow between the crosshead and the plane of complete recondensation, with more or less fine dispersion of the vapor in the liquid. However, at any moment, the volume of vapor present in the departure line is equal to the volume of water entering the channel since t_3 = 80 ms. Given the lower average density of two-phase fluid, the hydrostatic pressure at the point of main pump suction decreases.

t_4 = 260 Stoppage of the chain reaction (250 ms after the rod drop order).
Volume of water that has entered the channel = 96 l.
Leakage conditions as previously.

t_4 = 3.4 a = pressure in the reflector can = 0.58 bar.

The source changer is filled up to the isolation valve V16.
Volume of water that has entered the channel: 1 m^3.
Volume of vapor present in the departure line = approximately 1 m^3.
The flow rate of the main pumps is still equal to 72% of the nominal flow rate.

The hydrostatic pressure in the suction line of the main pumps is above 0.607 bars, considering the levels indicated in figure 3 and the length of the vapor plug in the 8 m pipes. In fact, since the flow rate is still 3.6 m/s (72% of the nominal rate which is 5 m/s), it appears improbable that all the vapor is in the descending line. A portion of the vapor will be carried into the horizontal line, which increases the static pressure at the level of pump suction.

t_5 = 10 s Order to close the safety valve. Its closure does not modify the status of the system.

3.3. Filling of the Source Changer

Considering the hypotheses summarized above, the first volume of water enters the channel at the velocity of 26.6 m/s. The volumes entering later are slower. Given the impossibility of giving water tensile and shearing stresses that could slow down the first volume that has entered, jet shrinking and dispersion effects can be expected.

The wall limiting the rear of the source changer containment is at a distance of approximately 12 m from the nose of the channel. The time Δt required for the fastest volume of 26.6 m/s to cover the 12 meters is:

$$\Delta t = \frac{12}{26.6} \text{ s} = 0.45 \text{ s}$$

A free horizontal jet, subjected to gravity, drops approximately 1 m vertically in 0.45 s. This means that the jet that enters the channel grazes the channel and source changer walls. The containment is filled by distribution of the leak water in a flow that is more or less free and, in any case, at a relatively slow velocity between the water and the walls.

The result of this is a slowing down of the leak rate as the containment is filled. This slowing down is accentuated by the multitude of sharp corners and complex shaped subassemblies.

Consequently, the filling velocity of the second phase indicated in table AII is very pessimistic, particularly concerning the end of filling. Given the slowing effect and the mechanical strength of the containment (sealed to the secondary vacuum after filling to 5 bars), the containment retains its integrity until filling is completed. The leak water remains contained in the source changer/channel unit.

3.4. Pressurization of the Reflector Can

All of the high points in the main circuit involving the channels and the equipment placed in the upper structure are connected to a collector which is connected to the gas "sky" of the expansion vessel. (The pressurization pumps aspirate the heavy water at the bottom of the expansion vessel and discharge it into the crosshead of the departure line).

Figure 5 shows a simplified schematic drawing of the placement of the pressurization circuit in the Reactor building. The piping located between the pile-unit and the pressurization casemate are placed horizontally in the water of the pool and channels 1, 2, and 3 over a distance of approximately 30 m.

The "sky" of the expansion vessel is connected to a facility that makes it possible to maintain the pressure (approximately 1 bar) using a reserve of 70 Nm^3 of helium.

When the pressure drops in the reflector can, the discharge pressure of the pressurization pumps decreases and their flow rate increases. However, the flow rate, even increased, remains negligeable compared to the leak flow rate.

On the other hand, depressurization modifies the flow regime in the line (56 mm I.D.) located between the high points of the upper structure and the expansion vessel "sky." At a normal regime, the pressure in the reflector can is approximately 4 bars; in the vessel "sky", approximately 1 bar. Flow rate limitation is handled by a diaphragm placed in the line near the expansion vessel. Considering the level difference between the expansion vessel and the axis of channel H9 (approximately 11.5 m), "equilibrium" exists when the pressure in the reflector can has reached approximately 1.3 bar, or 56 ms after channel failure.

The normal flow velocity, approximately 2 m/s, in the line decreases gradually and the flow direction is inverted. Given the connection of the line to the gas "sky" of the vessel, there is aspiration of helium, which causes the diaphragm to be reached quickly by the "gas plug", greatly reducing the head loss.

In order to have an order of magnitude for the time required to replace the water plug by a gas plug, the draining time of a smooth horizontal tube was calculataed (see Appendix B). Since the purpose is limited to the order of magnitude of the time required, the calculation does not take into account the head loss and the effect of the vertical parts of the line.

The result shows that the draining time is approximately 6 s and the velocity of the last small volume leaving the line is approximately 10 m/s.

Considering the simplifications in the calculation, this time should be increased in order to have the real conditions. However, the result is that complete drainage can be reached 10 to 15 seconds after the channel fails. At that time, the flow rate of the main pumps is approximately 50% (10 s) to 30% (20 s) of the nominal rate.

As the helium arrives in the reflector can, the vapor condenses and gradually disappears. The helium accumulates at first at the top of the reflector can. When the gas layer introduced reaches approximately 10 cm (0.5 m^3 at about 0.5 bars [pressure]), the helium is aspirated by the suction basket and rises in the crosshead of the depaerture line, gradually replacing the heavy water vapor.

When all of the vapor has been recondensed, the pressure level in the circuit rises to reach 1 bar at the point of interface between the heavy water and the helium.

3.5. Evacuation of the Residual Power

The main pump flywheels handle the proper cooling of the fuel element during the entire phase of filling the source changer, despite depressurization of the reflector can: 10 seconds after the main pumps stop, their flow rate is 48% of the nominal flow rate. For a residual power of 2 MW to be evacuated, the water heats up by approximately 1.5° C as it passes through the fuel element.

As the pump rate decreases even further, changes in the cooling regime must be taken into account.

Slowing of the water in the fuel element decreases the head loss to a considerable extent (see Appendix C). Figure 6 shows this head loss as a function of the time after the pumps stop. After 4 seconds, the head loss has already dropped from 10 to 5 bars and, after 10 seconds, it reaches approximately 2.25 bars.

The pressure difference on either side of the natural convection valve seats that is required to close them is approximately 1.1 bars and that of the siphon-breaker valve is approximately 1.8 bars (Appendix D). This means that the valves begin to open when the head loss in the fuel element reaches these values. The time corresponding to 1.8 bar on figure 6 is 12 to 14 seconds. The other valves open immediately thereafter. From that moment on, the by-pass constituted by the open valves drastically decreases the flow rate in the fuel element and cooling thereafter is done by natural convection.

Remember that, after the helium arrives in the reflecting can 10 to 15 seconds later, the pressure the time of changeover to natural convection [cooling] is between approximately 0.6 and 1 bar.

Consequently, since changeover to natural convection takes place from nominal power of the reactor, it is possible that the pressure level would be so low that phenomena such as local boiling cannot be excluded as possibilities.

3.4. Status of the Reactor after Valve Opening

The gaseous phase tends to accumulate in the top parts of the circuit. After time for balancing, the entire upper part of the upper structure will be filled with helium with a maximum volume of 1 m^3.

This means that the top of the stack and the water arrival line are partially filled with helium as well as all the high points of the upper structure.

The heavy water level is established temporarily above the crosshead of the departure line. The three natural convention valves (CN) are under water and operational, the CB valve for cooling of the control rod is under water with possibly a helium plug in the crosshead of the CRAB circuit, which would prohibit its operation. On the other hand, the siphon-breaker valve is uncovered.

Subsequently, the reflector can refills with heavy water because of the action of the pressurization pumps and additions to the expansion vessel from the heavy water storage tanks.

4. ABSTRACT

The loss of seal of the H9 channel in vacuum, freeing the entire cross section of the front part, leads to a fast leak that progresses rapidly. The effect of depressurizing the reflector can leads to shutdown of the shutdown rod pumps. The source changer associated with the channel fills completely before the valve closes. All of the leak water remains contained within the source changer containment. After the valves open, cooling of the fuel element is handled by natural convection, requiring a reversal of the flow between the plates. This change over, which takes place at a relatively low pressure level, could lead to local boiling in the fuel element. Consequently, irreversible transformations cannot be excluded as possibilities for the fuel element and even for the control rod.

Subsequently, the can is refilled with heavy water with establishment of the usual pressure levels.

[signature]

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APPENDIX A

CALCULATION OF THE SEQUENCE OF EVENTS WHEN THE H9 CHANNEL FAILS

For a perfect liquid, the sum of the static pressure p_{stat}, the dynamic pressure p_{dyn} and the hydrostatic pressure p_H is constant along a line of flow.

$$P_{stat} + P_{dyn} + P_H = Cte \quad (1)$$

$$P_{dyn} = \frac{\zeta}{2} V^2 \quad (2)$$

$$P_H = \zeta \cdot g \cdot H \quad (3)$$

V Flow velocity
ζ Density of fluid ($1.1 \cdot 10^3$ kg/m³)
g Acceleration (9.81 m/s²)
H Height

(2), (3) → (1):

$$P_{stat} + \frac{\zeta}{2} V^2 + \zeta \cdot g \cdot H = Cte \quad (4)$$

Let us apply equation (4) to a horizontal flow line between the reflector can a (far from the entry orifice, Va = 0) and the entry orifice i at the moment of failure:

$$Pa + \frac{\zeta}{2} + Va^2 + \zeta \cdot g \cdot Ha = P_i + \frac{\zeta}{2} V^2 + \zeta \cdot g \cdot H$$

$$P_a - p_i = \frac{\zeta}{2} V^2$$

where $V^2 = \sqrt{\frac{2(p_a - p_i)}{\zeta}}$

The law of the depresssurization of the reflector can [2] determines the evolution of the pressure p_a.

Removal of 12.5 l leads to a pressure drop of 1 bar.

$$C = \frac{12.5 \cdot 10^{-3}\ m^3}{bar}$$

A plug of length X entering in a cylindrical channel with a diameter D has the following volume:

$$V = \frac{\pi}{4} D^2 \cdot X \qquad (6)$$

The removal of V from the reflector can with a static pressure of p_{ao} leads to establishment of the pressure p_a:

$$P_a = p_{ao} - \frac{V}{C} = P_{ao} - \frac{\pi D^2}{4} \frac{X}{C} \qquad (7)$$

The drop in pressure p_a for a plug with a length of ΔX is:

$$\Delta P_a = \frac{\pi D^2}{4C} \Delta X \tag{8}$$

The flow velocity V is:

$$V = \Delta X / \Delta t \tag{9}$$

With Δt being the time interval

(9) $\longrightarrow$ (8)

$$\Delta P_a = - \frac{\pi D^2}{4C} v \Delta t \tag{10}$$

The volume of water entering the channel during Δt is:

$$\Delta V = \frac{\pi D^2}{4} \cdot \Delta X = \frac{\pi D^2}{4} v \cdot \Delta t \tag{11}$$

The volume of water V that has entered the channel since failure is:

$$V = \sum_{\Delta t} \Delta V \tag{12}$$

The pressure in the source changer containment is constant and corresponds to the relative vapor pressure at 50° C (heavy water temperature in the reflector can [1]).

$P_i = P_{io} = 0.112$ bar = const.

Equations used for the calculation:

Time t_o = failure	Δt	t_1
$P_{ao} = 4$ bars	$\Delta P_a = \frac{\pi D^2}{4C} v \, \Delta t$ (10)	$P_{ao} - \Delta P_a = P_{a1}$
$P_{io} = 0{,}112$ bar	$\Delta P_i = 0$	P_i
$v_o = \sqrt{\frac{2\,(P_{ao} - P_{io})}{\rho}}$ (5)		$v_1 = \sqrt{\frac{2(P_a - P_i)}{\rho}}$ (5)
$\Delta V = 0$		$\Delta V_1 = \frac{\pi D^2}{4} v \Delta t$ (11)
$V_1 = 0$		$V_1 = \sum \Delta V$ (12)

Starting with the status of the system at the beginning t_o, the calculation was made step by step for $\Delta t = 2 \cdot 10^{-3}$ s assuming that the velocity of flow between t_n and t_{n+1} can be considered constant. The same calculation for $\Delta t = 10^{-3}$ s produces practically the same results.

The results are given on tables AI and AII.

The pressures p_a on the table are relative to the level of the H9 channel axis. The static pressures in the other zones can be calculated from equation (4). The "high point" of the low pressure portion of the primary circuit is constituted by the departure line crosshead of the main circuit where the flow velocity is 5 m/s.

Let us apply (4) to a line of water between a point in the reflector can located at the level of the H9 channel axis and the high point of the crosshead (ΔH = 3 m).

$$p_a + 0 = p_{stat} + \frac{\zeta}{2} v^2 + \zeta \cdot g \cdot H \qquad (4)$$

$$p_a = p_{stat} + \frac{1.1 \cdot 10^3 \cdot 25N}{2m^2} + 1.1 \cdot 10^3 \cdot 9.81 \cdot 3N/m^2$$

$$= p_{stat} + 1.38 \cdot 10^4 \frac{N}{m^2} + 3.24 \cdot 10^4 \frac{N}{m^2}$$

$$p_a = p_{stat} + (0.138 + 0.324) \text{ bar} \qquad (13)$$

When the static pressure p_{stat} equals the saturation pressure of the heavy water at 50° C, there is a beginning of cavitation. At that time, pressure p_a is:

$$p_a = (0.112 + 0.138 + 0.324) \text{ bar}$$

$$p_a = 0.574 \text{ bar}$$

After the beginning of cavitation, the pressure in the reflector can remains constant. The volume of water entering the channel is compensated by a vapor bubble of the same volume that will be carried into the departure line located downstream of the crosshead.

As the vapor bubble is carried by the current, there is recondensation, since the hydrostatic pressure increases in the vertical line.

The flow regime remains the same between the beginning of cavitation and the complete refilling of the source changer containment (second phase).

TABLE AI: SEQUENCE OF THE FAST LEAK IN THE H9 CHANNEL

(First Phase)

TABLE AII: SEQUENCE OF THE FAST LEAK IN THE H9 CHANNEL

(First and Second Phases)

Ruptures	BAUER	A I
Déroulement	Stations	

TABLEAU A I : DEROULEMENT DE LA FUITE A GROS DEBIT DANS H9

1ère PHASE

t	[mn]	0	2	4	6	8	10	12	14	16	18	20	22	24
pa	[bar]	4	3.87	3.75	3.62	3.50	3,38	3,27	3,15	3.04	2,93	2,82	2,71	2.60
pi	[bar]	[illegible]	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11
v	[illegible]	26,6	26,2	25,7	25,27	24,8	24,4	23,95	23,5	23,1	22,6	22,2	21,8	21,3
m'	[illegible]	1,6	1,57	1,54	1,52	1,49	1,46	1,43	1,41	1,38	1,36	1,33	1,31	1,28
l	[illegible]	0	1,6	3.17	4,71	6,22	7,71	9,18	10,62	12,0	13,41	14,8	16,1	17,4

t	[mn]	[illegible]	28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
pa	[illegible]	[illegible]	[illegible]	[illegible]	2,21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
pi	[illegible]	0,11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
v	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
m'	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
l	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Rupture H9	BAUER	A II
Déroulement		Δt = 4ms Δt = 1sec

TABLEAU A II : DEROULEMENT DE LA FUITE A GROS DEBIT DANS H9

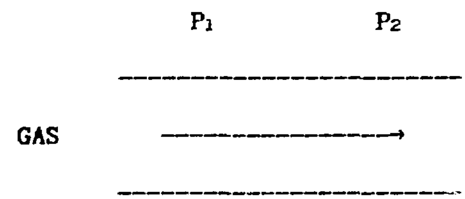
1ère et 2ème PHASES

t	[ms]	48	52	56	60	64	68	72	76	80				
Pa	[bar]	1,52	1.44	1.29	1,15	1.02	0,90	0.782	0,68	0.58				
Pi	[bar]	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11				
v	[m/s]	16.0	15.6	14.7	13.8	12.9	11,96	11.1	10,2	9,2		1ère phase		
dV	[l]	0.96	1,87	1.76	1.65	1.54	1.44	1,33	1,22	1.11				
V	[l]	31.0	32,9	34.8	36.6	38.2	39,8	41,2	42.5	43,8				
t	[s]	0,08	1	2	3	3,4								
Pa	[bar]	0,58	0,58	0,58	0,58	0,58								
pi	[bar]	0,11	0,11	0,11	0,11	0,58								
v	[m/s]	9,2	9,2	9,2	9.2	—		2ème phase						
V̇	[l/s]	289	289	289	289	—								
V	[l]	43,8	310	600	889	1000								

A 7.

APPENDIX B

DRAINAGE VELOCITY IN THE HIGH POINT LINE



A horizontal tube of constant cross section filled with a perfect liquid is assumed to be exposed to a pressure differential $P_1 - P_2 > 0$.

At time $t_0 = 0$, the velocity of the water plug contained in the pipe is assumed to be equal to zero.

$V_0 = 0$

The water plug starts moving under the effect of acceleration to the pressure difference $p_1 - p_2$. During flow, the volume of water leaving the pipe will be replaced on the other side by gas. The pressures p_1 and p_2 are assumed to be constant.

The increase of the kinetic energy of the plug dE_c is due to the force F exercises on the plug along the path dx.

$$dE_c = Fdx \qquad (1)$$

The kinetic energy can be expressed as follows:

$$E_c = \frac{1}{2} m \cdot v^2 \quad \text{with } m \text{ - mass} \qquad (2)$$

V - velocity

$$dE = \frac{1}{2} (m2Vdv + v^2 dm) \qquad (3)$$

The force exerted on the plug is:

$$F = (P_1 - P_2)\, S \qquad P_1, P_2 \text{ - pressures} \quad (4)$$

S - pipe cross section

The mass m of a water plug with a cross section S and a length X is given by the following:

$$m = S \cdot X \cdot \zeta \qquad \zeta \text{ - density} \qquad (5)$$

$$dm = S \cdot dx \qquad (6)$$

Equations (1), (3), (4) and (6):

$$\frac{1}{2} (2mVdV = V^2\ dm) = (P_1 - P_2)\, S\, dx$$

$$Sx\zeta VdV + V^2\ S\zeta dx = (p_1 - P_2)\, S\, dx$$

$$dV = \frac{P_1 - P_2}{\zeta x} \frac{dx}{V} - \frac{V}{x}\, dx \qquad (7)$$

The length dx can be expressed by the velocity and the time interval considered dt.

$$dx = Vdt \qquad (8)$$

(7) + (8):

$$dV = \frac{P_1 - P_2}{\zeta x}\, dt - \frac{V^2}{x}\, dt \qquad (9)$$

Means of calculation: (8) + (9)

$t_0 = 0$	Δt ....1 ms	$t_1 = 1$ ms	
$V = V_0 = 0$	ΔV = (9) for x_0	$V_1 = V_0 + \Delta V$	etc....
$x = x_0 = 30$ m	Δx ... (8) for V_1	$x_1 = x_0 + \Delta x$	

The calculation was performed step by step for Δt = 1 ms and a pipe length of 30 m.

RESULTS: At the time the pipe is completely refilled with gas, the velocity of the last small volume of water is 10.16 m/s. The time required for complete drainage is 5.91 seconds.

APPENDIX C

FUEL ELEMENT HEAD LOSS

The head loss Δp of the fuel element under normal cooling conditions is given by the following:

$$\Delta\pi = \xi \frac{\zeta}{2} \qquad (1)$$

ξ ...coefficient

ζ ...density

V ...flow velocity between plates

Assuming that ξ and ζ remain more or less constant [3] during the gradual drop of the flow rate through the fuel element, equation (1) becomes:

$$\Delta p = C_1 V^2 \qquad (2)$$

C_1 ... constant

The velocity V is proportional to the pump flow rate d:

$$V = C_2 d \qquad (3)$$

C_2 ... constant

(3) + (2) :

$$\Delta p = C_3 d^2 \qquad C_3 \ldots \text{constant} \tag{4}$$

By standardizing (4) by the nominal conditions δp_N = 10 bars and dN, we get:

$$\Delta p = 10 \text{ bars } \left(\frac{d}{d_N}\right)^2 \tag{5}$$

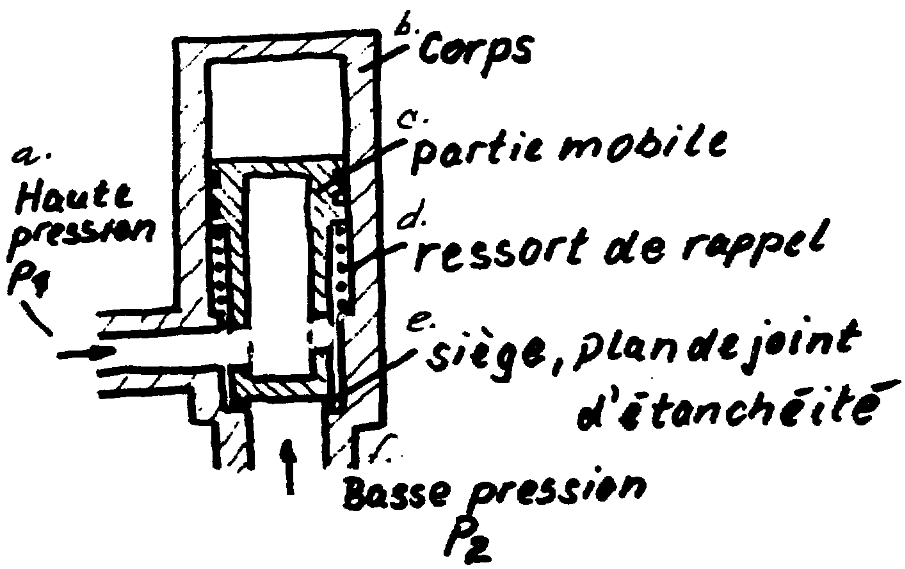
Equation (5) makes it possible to calculate the decrease of the fuel element head loss when the main pumps shut down, from date in figure 4, which makes it possible to determine when the natural convection (CN) and siphon-breaking (CS) shutters open.

The results are given in the form of the curve in figure 6.

APPENDIX D

OPENING OF NATURAL CONVECTION (CN), (CB) AND SIPHON-BREAKING (CS) SHUTTERS

The CN, CB and CS shutters, of identical design, can be shown in the closed status below:



Key:

a. High pressure p_1

b. Body

c. Mobile part

d. Recall spring

e. Seat, seal ring plane

f. Low pressure p_2

The mobile part, constituted of a hollow cylinder laterally pierced, rests on the seat which is part of the body of the shutter. The high pressure p_1 acting on the bottom of the mobile part, assures closure of the shutter despite the effect of the low pressure p_2 and of the recall spring acting in the direction of opening.

The zones acting on the mobile part are the following:

$$P_1 \cdot S = P_2 \cdot S - R + F - A = 0$$

With S free cross section of seat

R Spring force

F Force due to the weight itself

A Supporting force of seat

The shutter begins to open when the seat's supporting force becomes $A \leq 0$.

$$A = (P_1 - P_2)\, S + F - R \leq 0$$

or:

$$(P_1 - P_2) \leq \frac{R - F}{S}$$

For the CS shutter:

$$R = 1.3 \cdot 10^3 \text{ N}$$

$$F = 40 \text{ N}$$

$$S = 7.1 \cdot 10^{-3} \text{ m}^2$$

$$p_1 - p_2 \leq \frac{1.3 \cdot 10^4 - 40}{3.85 \cdot 10^{-3}} = 1.11 \text{ bar}$$

<u>RESULTS</u>

The siphon-breaking shutter opens when the difference between the high and low pressure opposite the seat becomes less than approximatly 1.8 bars. The corresponding value for the CN shutters is 1.1 bars.

FIGURES

Figure 1 Schematic of reactor with H9 channel

Key:

a. POOL
b. Center core
c. H9 Channel
d. Safety Valve
e. Changer containment
f. Collar
g. Concrete
h. Departure crosshead, CRAB D_2O circuit
i. Upper Structure
j. Reactor Valve
k. CB Shutter
l. D_2O Depart crosshead, main circuit
m. CS Shutter
n. CN Shutters
o. Suction basket
p. Fuel Element
q. Reflector can
r. CRAB departure line
s. Reflector can
t. D_2O arrival line, main circuit
u. D_2O departure line, main circuit
v. Isolation valve V16

Figure 2: Schematic of D_2O Primary Circuits

Key:

a. Exchanger, Shutdown Rod
b. Main exchangers
c. D_2O Purification
d. Pumps, Shutdown Rod
e. Main pumps
f. Diaphragm, Main flow measurement
g. Diaphragm, shutdown flow measure
h. Diaphragm, rod flow measurement
i. Siphon-breaker valve
j. Natural Convection Valve

Figure 3: Schematic with levels

a. Levels in [m] from the axis of channel H9

Figure 4: Decrease of the main pump flow rate after shutdown

a. Flow rate decrease d/d_N
b. Nominal flow rate
2140 m^3/h - 2 pumps
1540 m^3/h - 1 pump

Figure 5: Placement of pressurization circuit

Key:

a. High points
b. Reflector can
c. Connection
d. After depresurization
e. Normal
f. Expansion vessel
g. Pressurization pump

Figure 6: Head Loss of Fuel Element after Main Pumps Stop

a. Head loss Δp
b. Time after shutdown

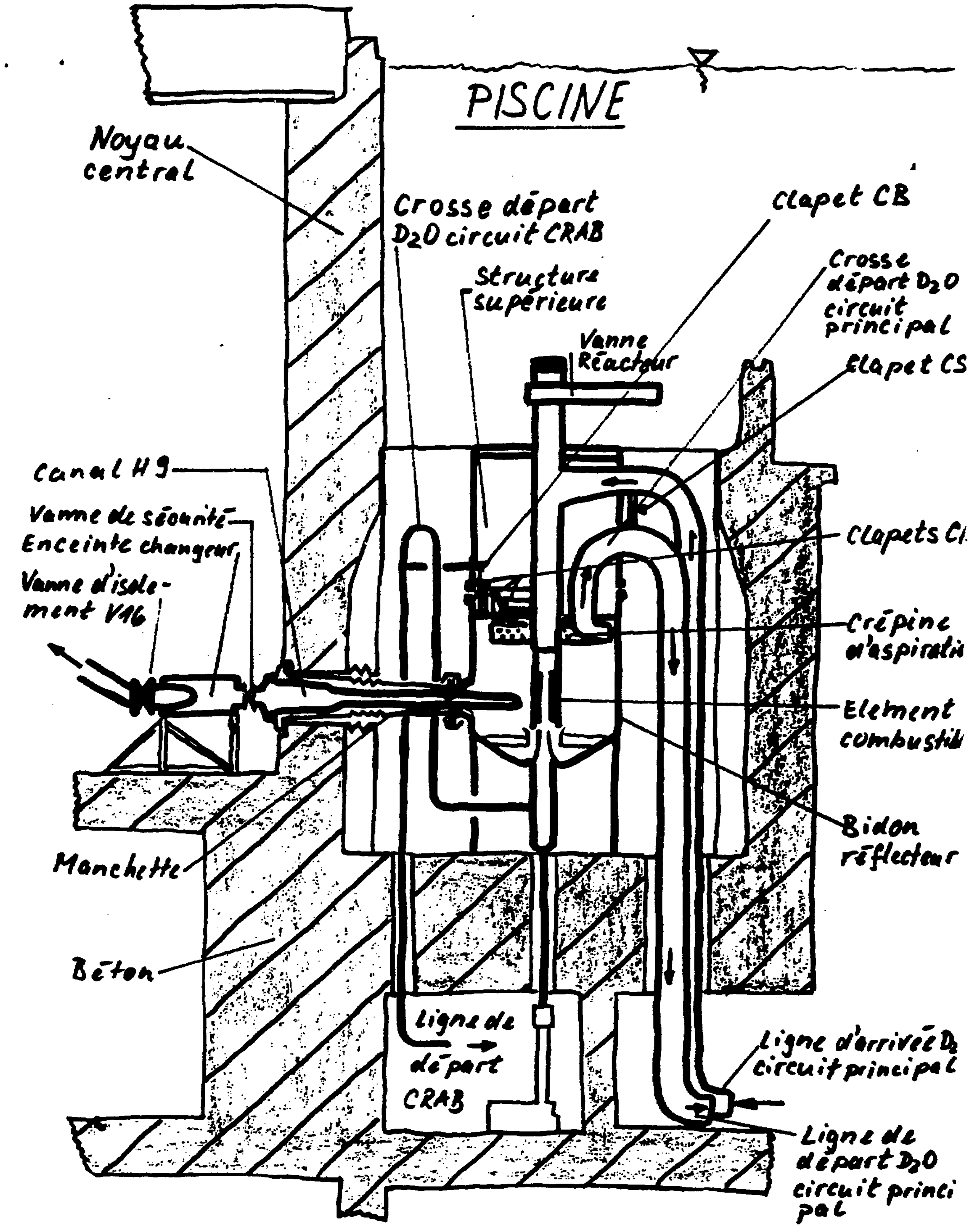


Fig. 1: Schéma du Réacteur avec H.9

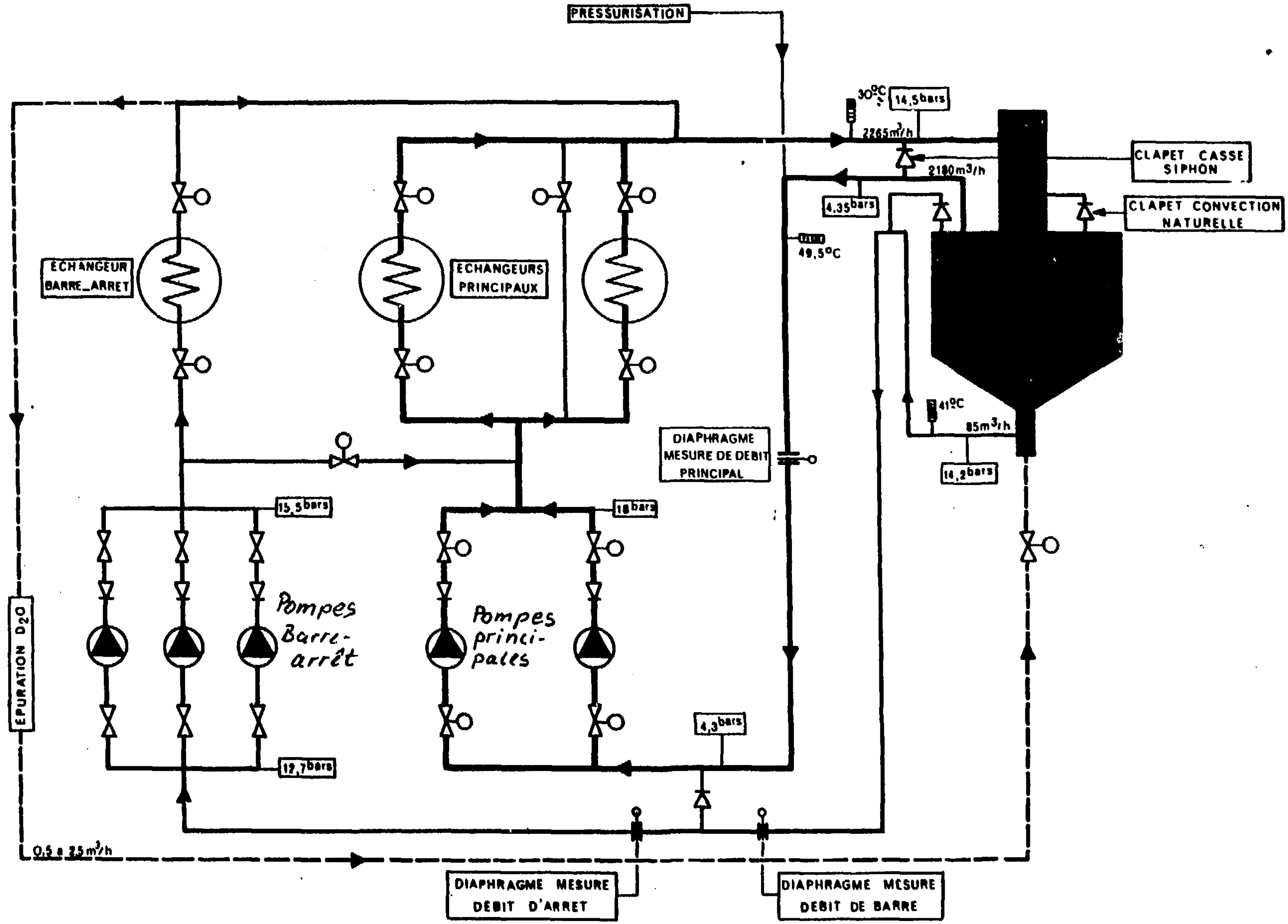


Fig. 2 : SCHEMA DE PRINCIPE DES CIRCUITS PRIMAIRES D_2O

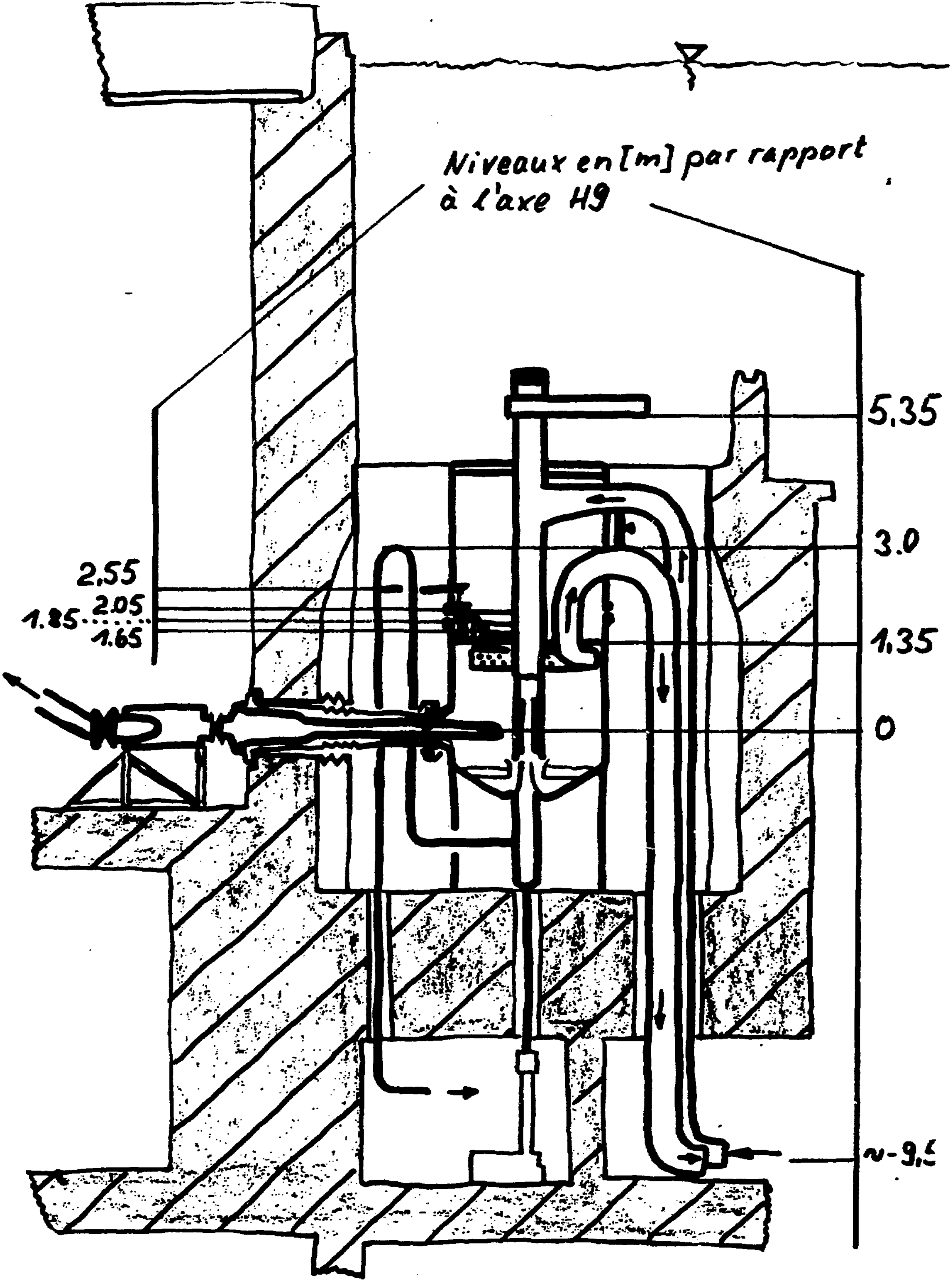


Fig.3: Schéma avec niveaux

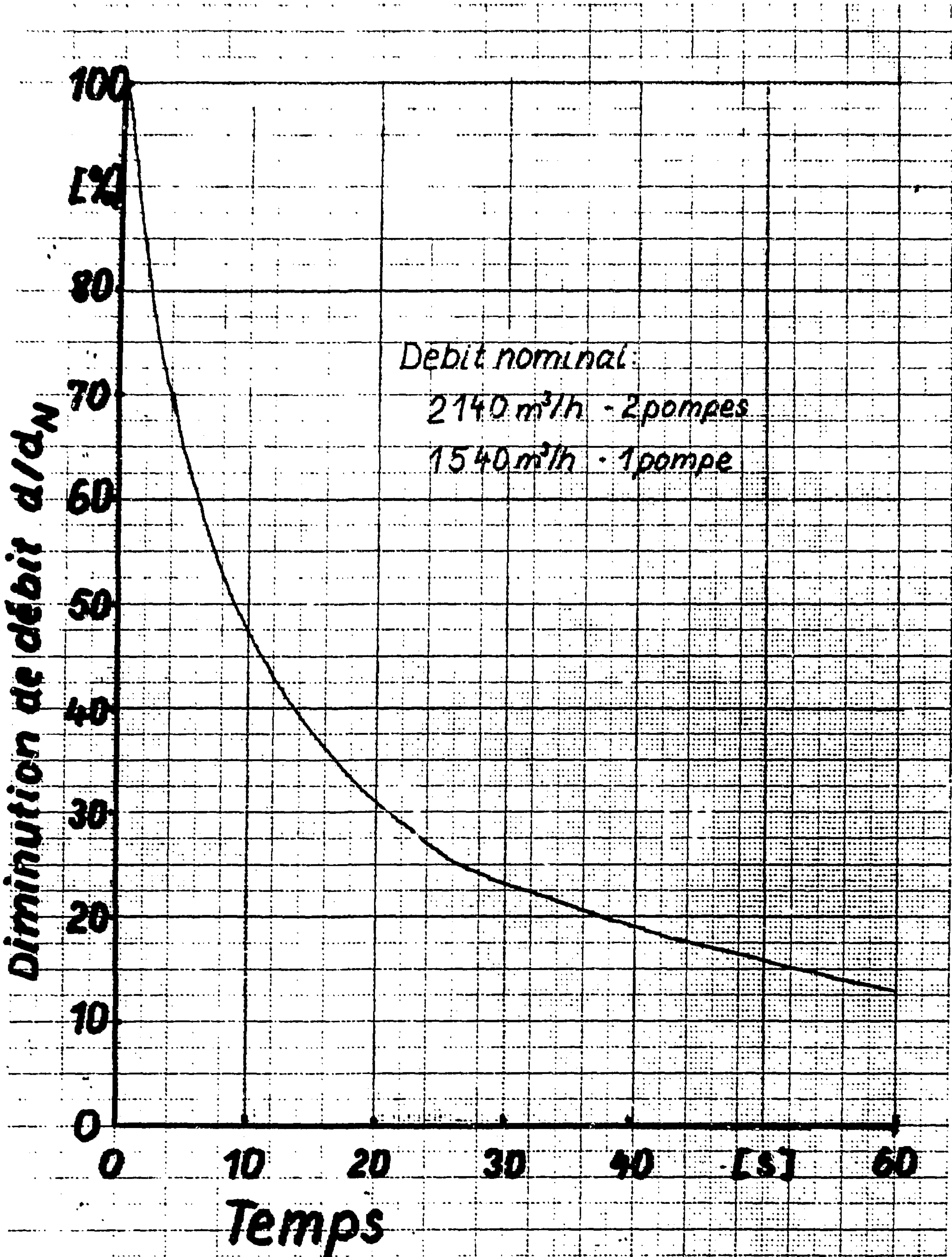


Fig. 4: Diminution du débit des pompes principales après l'arrêt

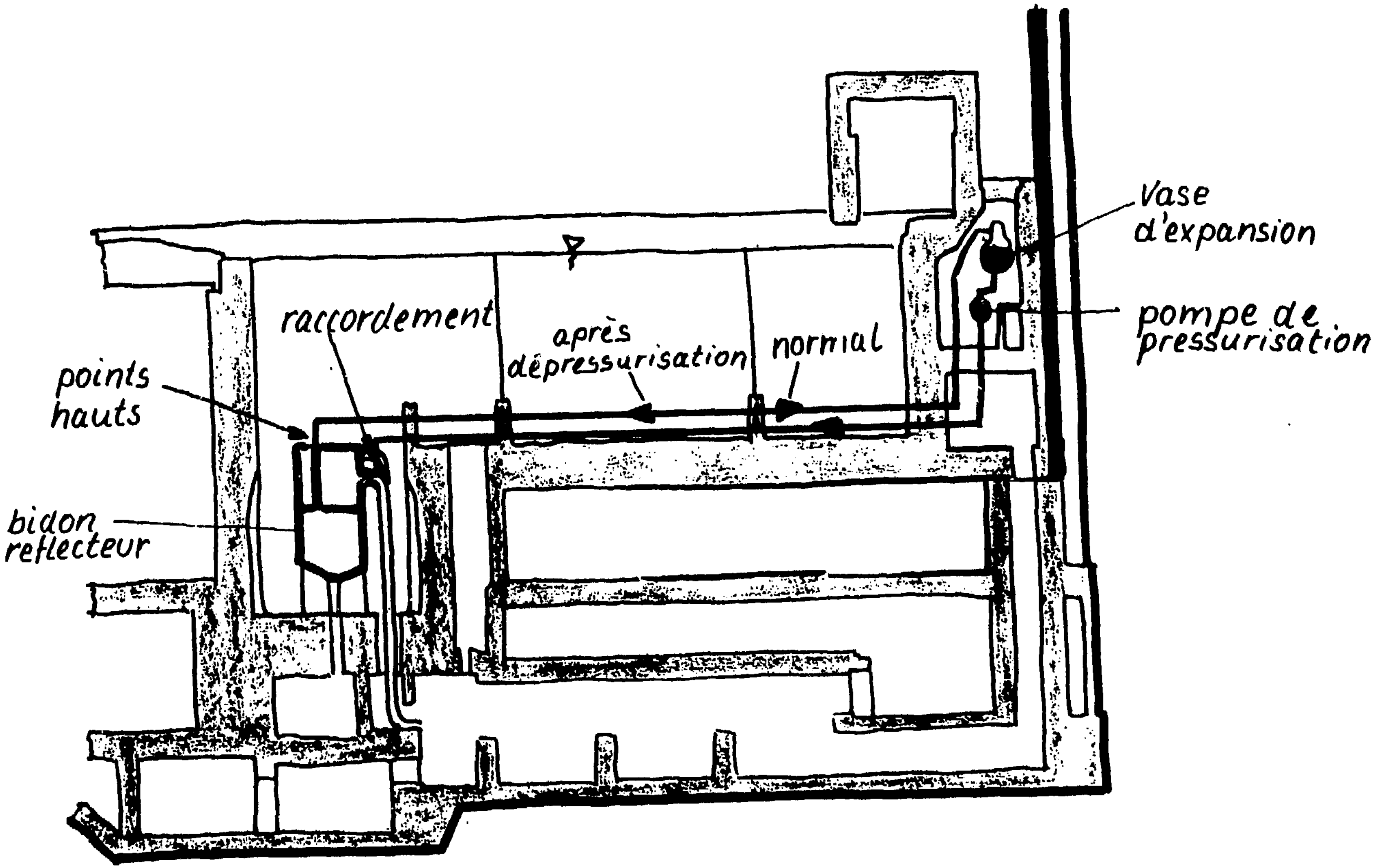


Fig.5 Implantation du circuit de pressurisation

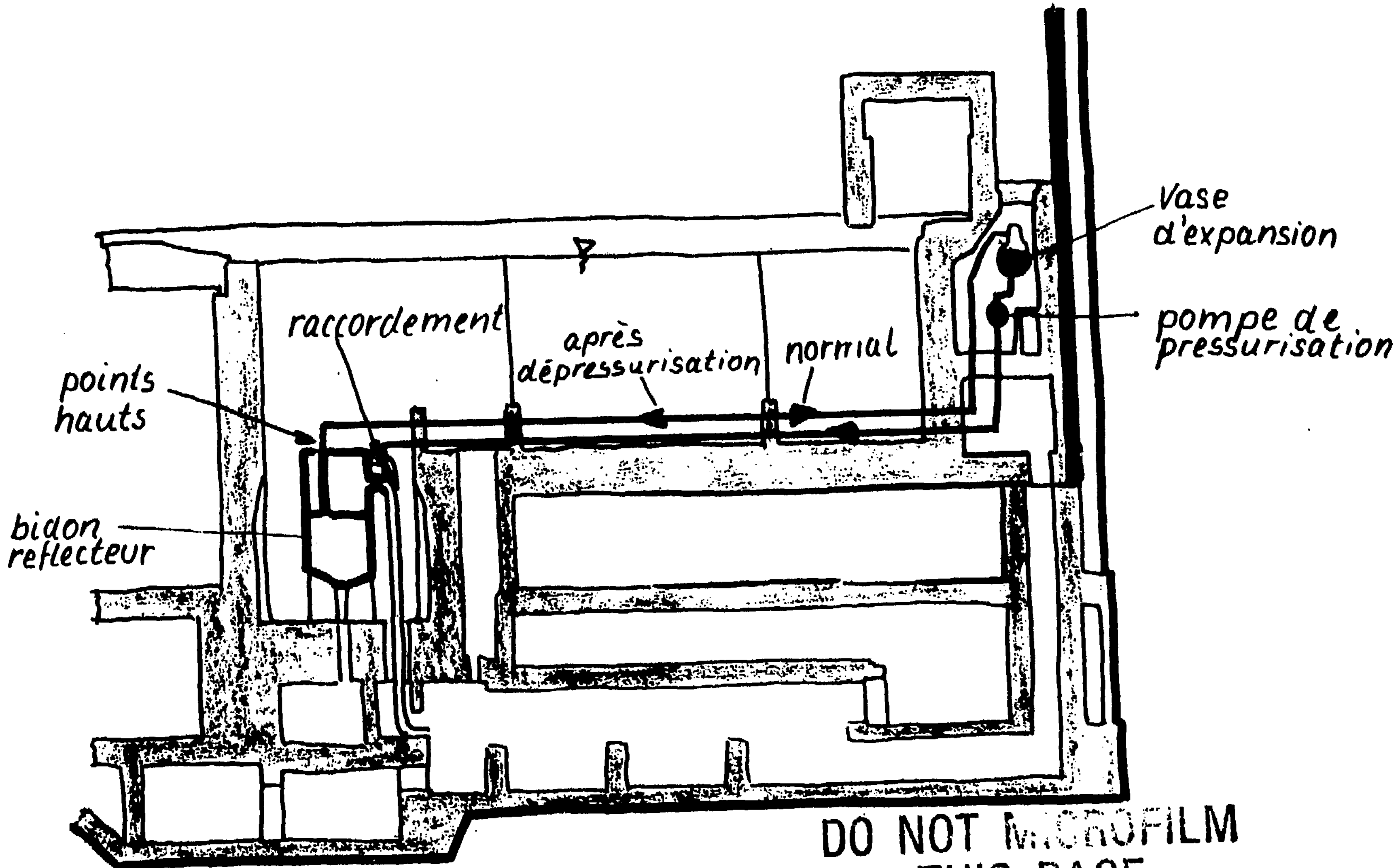


Fig.5 Implantation du circuit de pressurisation

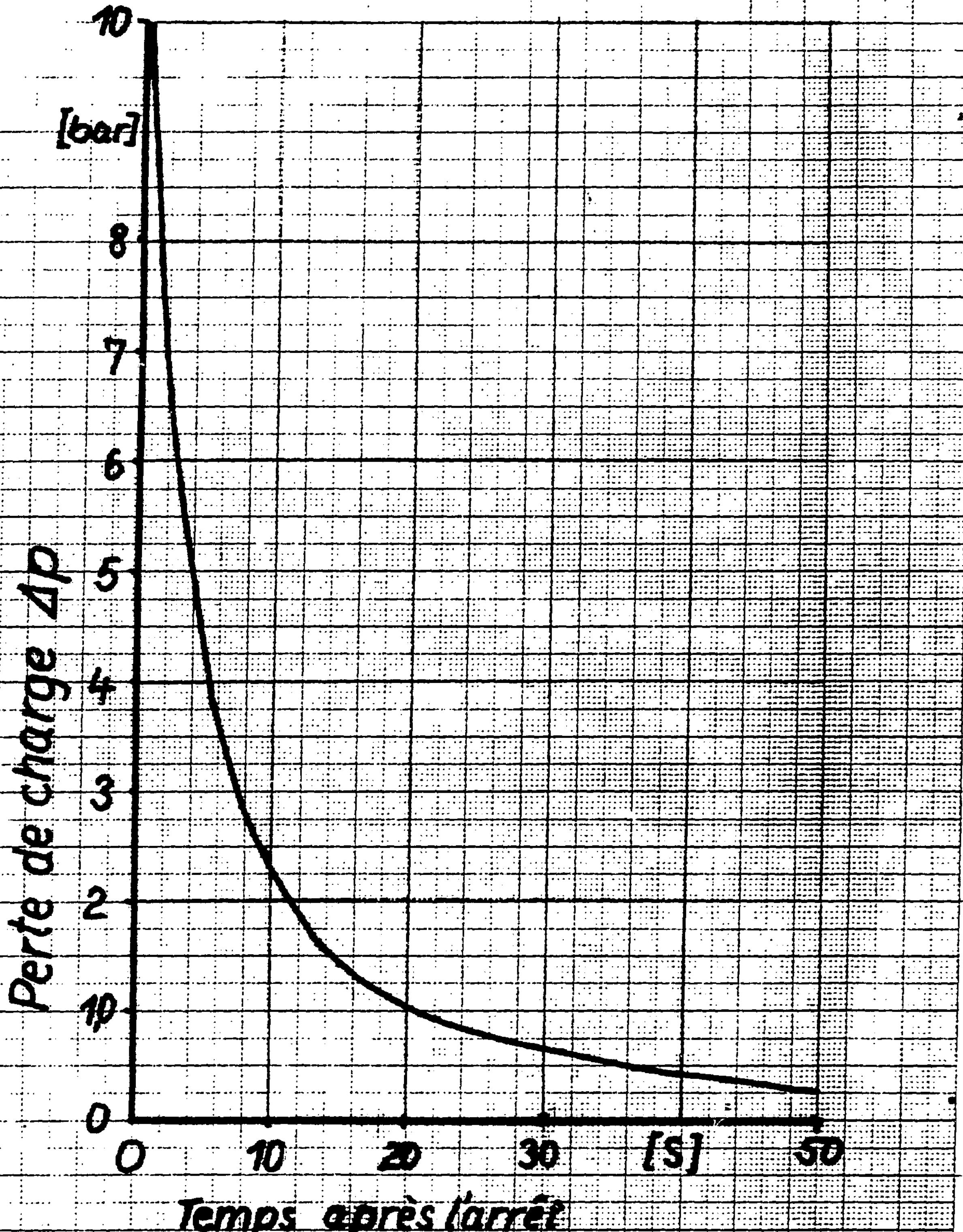


Fig.6 Perte de charge de l'élément combustible après l'arrêt des pompes principales