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Theoretical thermal-hydraulic investigations of the operational and safety features of the cold D_2-moderator for SINQ

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ABSTRACT

In order to be able to investigate the behaviour of the gas-liquid mixture in the rather complex vessel and pipe system of the cold D_2-moderator with heat exchanger and ballast volume, a computational model of the system has been set up. The model was first benchmarked against experimental data from the cold moderator mockup for the second cold source at the ILL Grenoble. It was then used to predict operational parameters such as pressure, velocity, moisture content and others of the system under normal conditions with the anticipated distribution of heat influx. Finally, the case of total loss of insulating vacuum was investigated.

I INTRODUCTION

As compared to the cold moderators of the existing spallation neutron sources, the one planned for SINQ is different in two respects:

- SINQ being a cw-source, the cold moderator is designed to give a high time average flux of cold neutrons. This implies the use of a large D_2-filled moderator vessel.
- The high beam power of SINQ (around 1 MW) together with the large moderator volume results in a high heat input during normal operation.

Although these conditions also prevail in research reactors, other considerations such as high energy radiation shielding prevent us from simply adapting an established cold moderator design but caused us to deviate sufficiently far from existing designs to make a detailed analysis of the thermal-hydraulic behaviour necessary. Part of the work has been reported earlier /1/. This paper gives an update to include recent results from a slightly improved computational model.

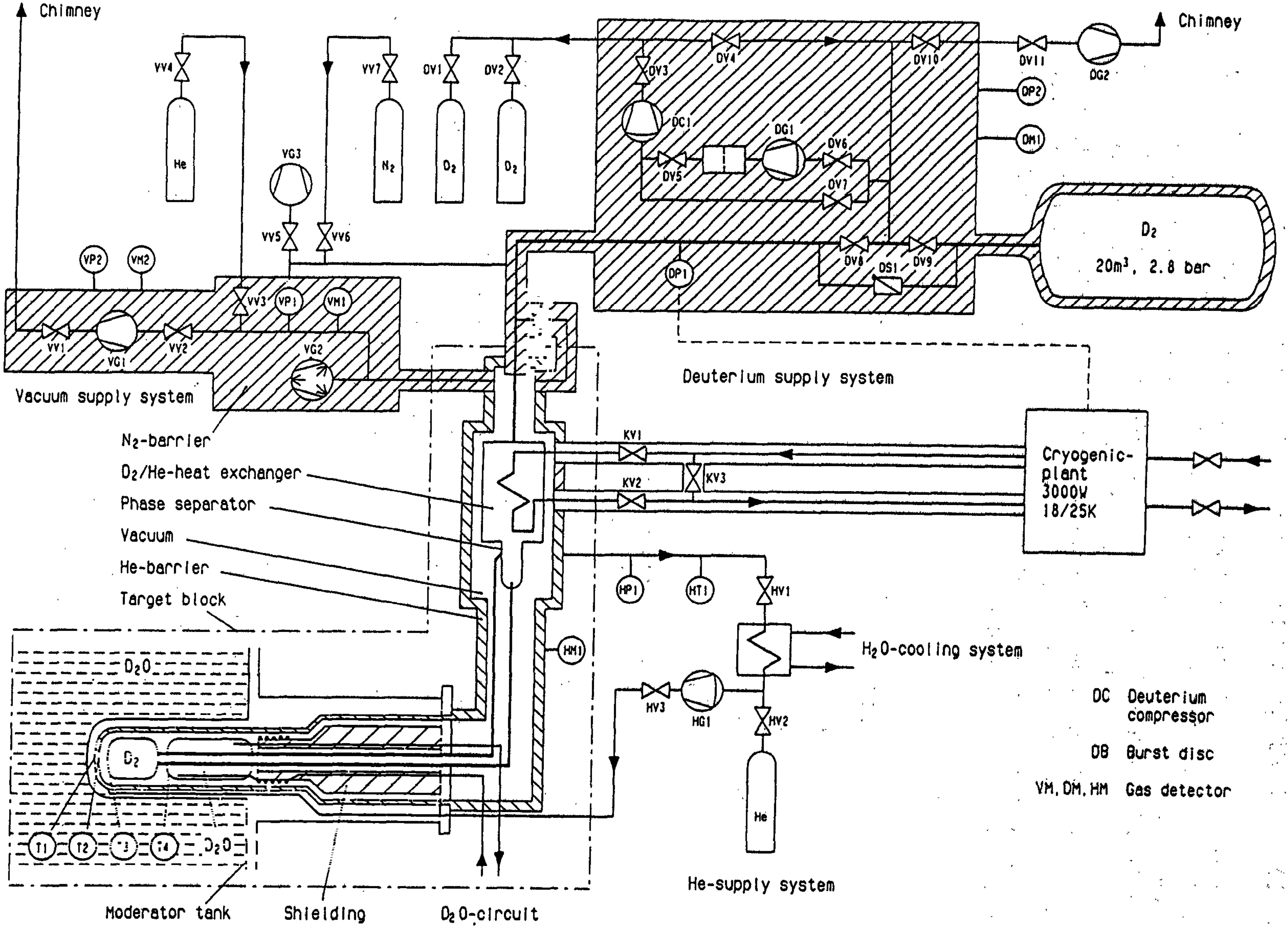

Fig. 1 Simplified diagram of the various subsystems of the D_2 cold moderator for SINQ. The cold part of the D_2 system consists of the moderator vessel, the phase separator - condenser volume and a pair of concentric pipes for circulation of the liquid and liquid-gas mixture.

II THE D_2-SYSTEM AND ITS MODEL REPRESENTATION

The technical concept of the SINQ-cold moderator system has been described elsewhere /1/, /2/. Fig. 1 shows a simplified diagram of the D_2- and auxiliary circuits. Only the D_2 part is considered in this work and is modelled as a system of three vessels representing the moderator, the phase-separator/heat exchanger and the ballast volume for the D_2-gas. These volumes are interconnected by pipes whose cross-sections have been fixed for the time being but may well be optimized as a result of ongoing calculations of the type described here. The model representation and the numbering of the pipe segments are shown in Fig. 2 and the corresponding dimensions given in Table 1. Pipe segments A and B are concentric with the forward flow (heat exchanger -to- moderator) through the inner pipe and return flow through the outer annulus.

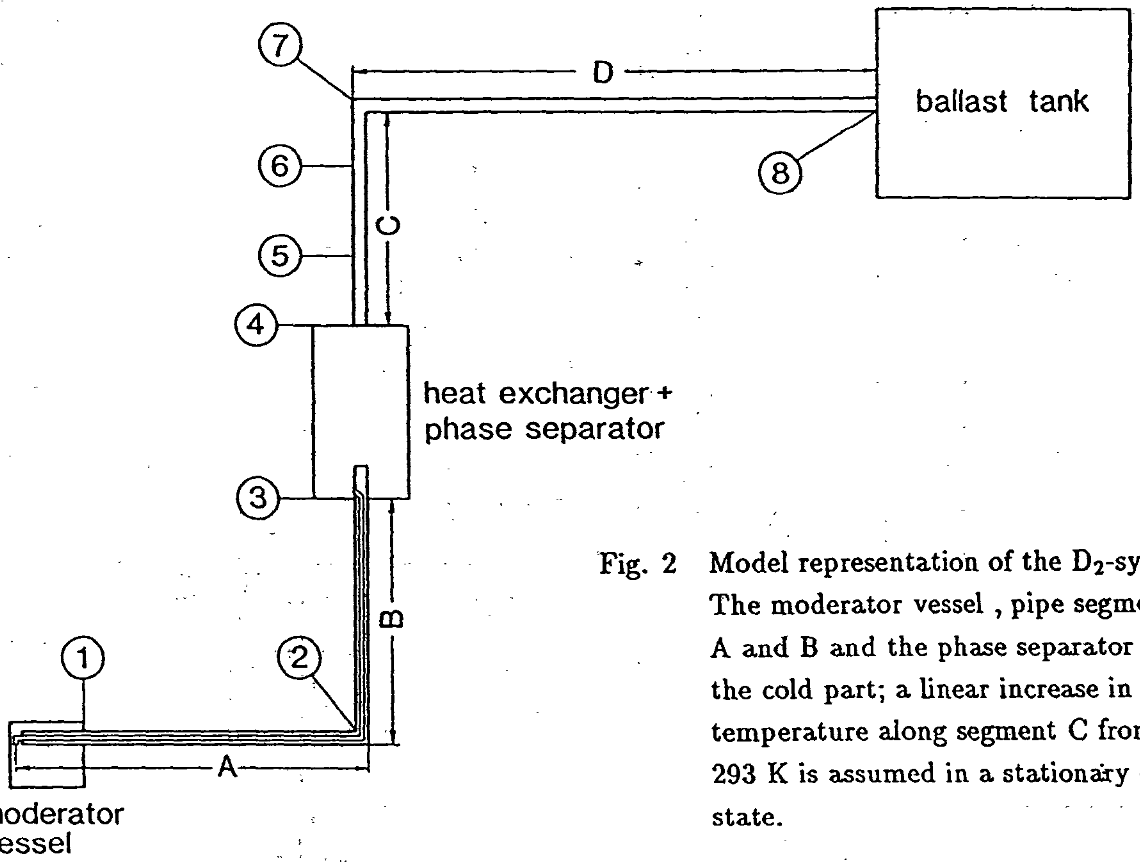

Fig. 2 Model representation of the D_2-system. The moderator vessel, pipe segments A and B and the phase separator comprise the cold part; a linear increase in temperature along segment C from 25 K to 293 K is assumed in a stationary operating state.

III THE COMPUTATIONAL MODEL

In the computational model, the three vessels are treated as "localized capacitors" where phase changes can take place and the mass content can vary. The connecting pipes are subdivided into individual elements with coupled thermodynamic properties. Coexistence of vapour and liquid and, as a new feature relative to the earlier calculations (/1/), heat input and superheated vapour is allowed in all volumes of the cold part of the system, whereas only vapour exists in the ballast volume and in pipe segments C and D.

Dynamic equilibria in mass, energy and forces are established between all neighbouring elements of the system. The corresponding coupled partial differential equations are replaced by difference equations and are applied to the finite elements. Integration is carried out numerically (with a FORTRAN programme).

The compressibility of the vapour and the variable temperatures of the superheated vapour are taken into account where appropriate.

In order to benchmark the model and to obtain realistic values for some poorly known parameters, the data given by Hoffmann /3/ for the ILL-test experiments were reproduced in a first step with very good agreement.

Volume of the moderator vessel	22.3 litres
Volume of the phase separator/heat exchanger	30.0 litres
Volume of the D_2-ballast tank	20 m^3
Length of pipe segment A	3.9 m
Inner diameter of outer pipe in segment A	4.5 cm
Outer diameter of inner pipe in segment A	2.0 cm
Length of pipe segment B	2.7 m
Inner diameter of outer pipe in segment B	5 cm
Outer diameter of inner pipe in segment B	2 cm
Length of pipe segment C	1.8 m
Inner diameter of pipe segment C	6.7 cm
Length of pipe segment D	55 m
Inner diameter of pipe segment D	9 cm

Table 1 Dimensions of the SINQ-D_2-system

IV RESULTS FOR STANDARD OPERATING CONDITIONS

A series of calculational runs was performed to obtain a feel for the stability of the model results and also for the behaviour of the system in the event of a perturbation. It was found that the system moved towards stable operating conditions when an arbitrary, but reasonable yet non-consistent set of start parameters was given for the various system variables.

One unknown in the system, which has an effect on the set of stable parameters and which could not be derived in a theoretical manner is the liquid content of the vapour at the point of entrance from the moderator vessel to the inner pipe of segment A.

This "dryness" of the returning medium is very difficult to estimate, since it will depend on the violence of boiling in the moderator vessel, on geometry and possibly other factors. In order to get a feeling for its effect, the assumption was made, that the dryness x is a linear function of the the height h of the nominally vapour-filled volume inside the moderator vessel, i.e.:

$$x \sim \frac{h}{D}$$

with D being the diameter of the moderator vessel (Fig. 3).

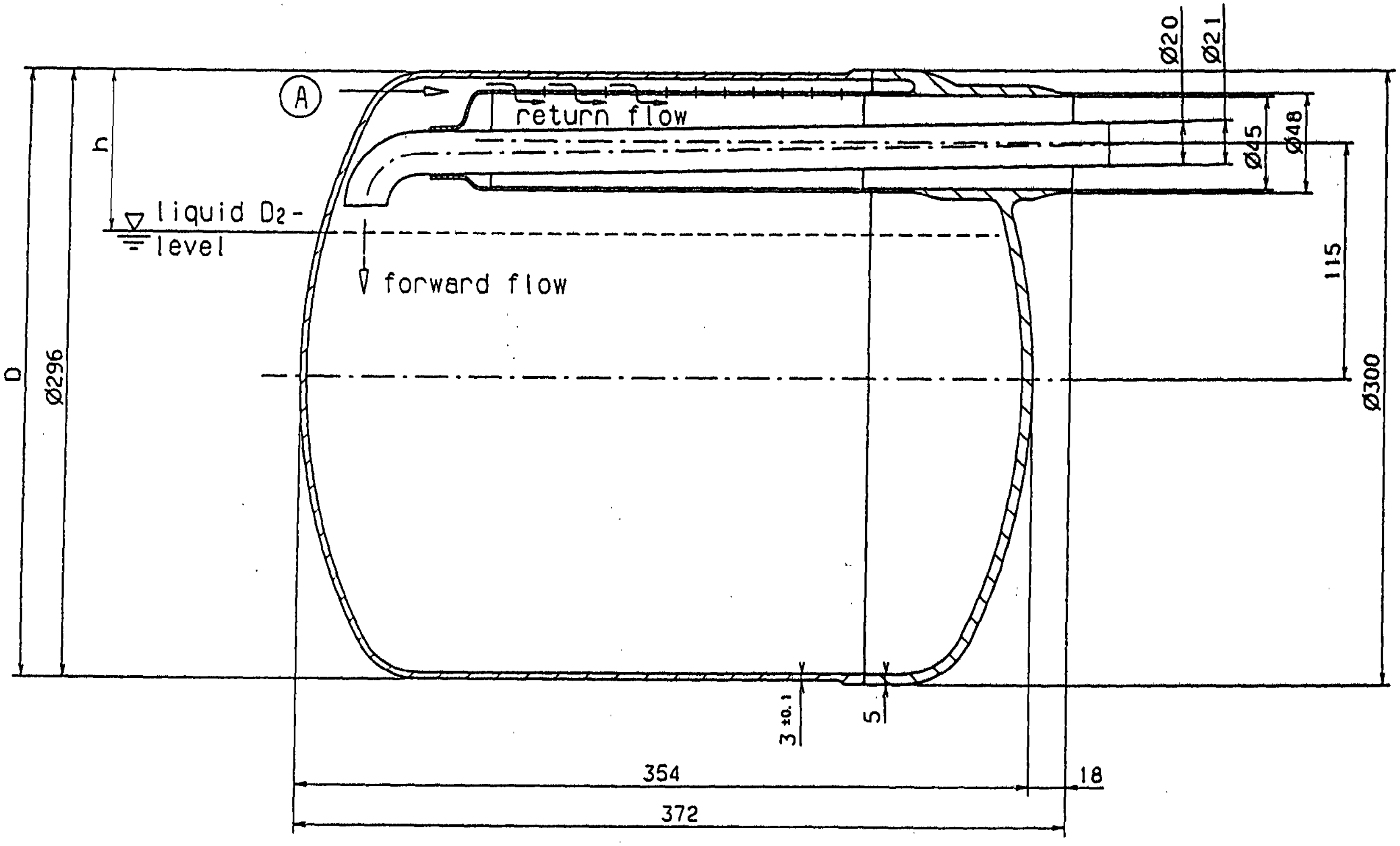

Fig. 3 Vertical section through the moderator vessel showing the definitions of h and D.

	t = 0	t = 20 sec			t = 30 sec			t = 60 sec		
		(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
Velocity of return flow (liquid-gas-mixture) (m/s)	0.58	2.77	2.26	2.067	2.536	2.264	2.160	2.26	2.26	2.25
Velocity of forward flow (liquid D_2) (m/s)	0.40	2.10	2.08	2.038	2.098	2.078	2.058	2.08	2.08	2.08
Mass fraction of vapour in return flow (%)	15	13.4	10.6	9.1	12.3	10.6	9.8	10.7	10.7	10.5
Return mass flow (g/s)	18.0	93.47	93.89	97.5	93.3	93.9	95.9	93.6	93.9	94.25
Forward mass flow (g/s)	18.0	94.7	93.7	91.9	94.6	93.7	92.8	93.78	93.66	93.52
Total mass of D_2 in moderator vessel (kg)	3.045	3.1	3.0	2.8	3.1	3.0	2.75	3.1	3.003	2.7
Total mass of vapour in moderator vessel (g)	3.045	2.042	3.989	8.75	1.760	3.990	9.705	1.44	3.99	10.7
Relative height of liquid level (1- h/D)	0.91	0.93	0.89	0.82	0.94	0.89	0.80	0.95	0.89	0.80
Pressure in moderator vessel (bars)	1.570	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57

Table 2 Variation of some parameters of the SINQ D_2-system as a function of time from an "arbitrary" set of starting values and under a heat input of 3 kW to the moderator vessel.

Three cases were considered (Fig. 4):

(a) x = 1 for $^h/_D = 0.5$, i.e. dry vapour if the vessel is less than half-full

(b) x = 1 for $^h/_D = 1$, i.e. dry vapour only if there is virtually no liquid volume in the vessel

(c) x = 0.5 for $^h/_D = 1$, i.e. there is still a 50 % liquid fraction in the return flow even at the moment, when a stationary liquid surface cannot be detected in the vessel any more

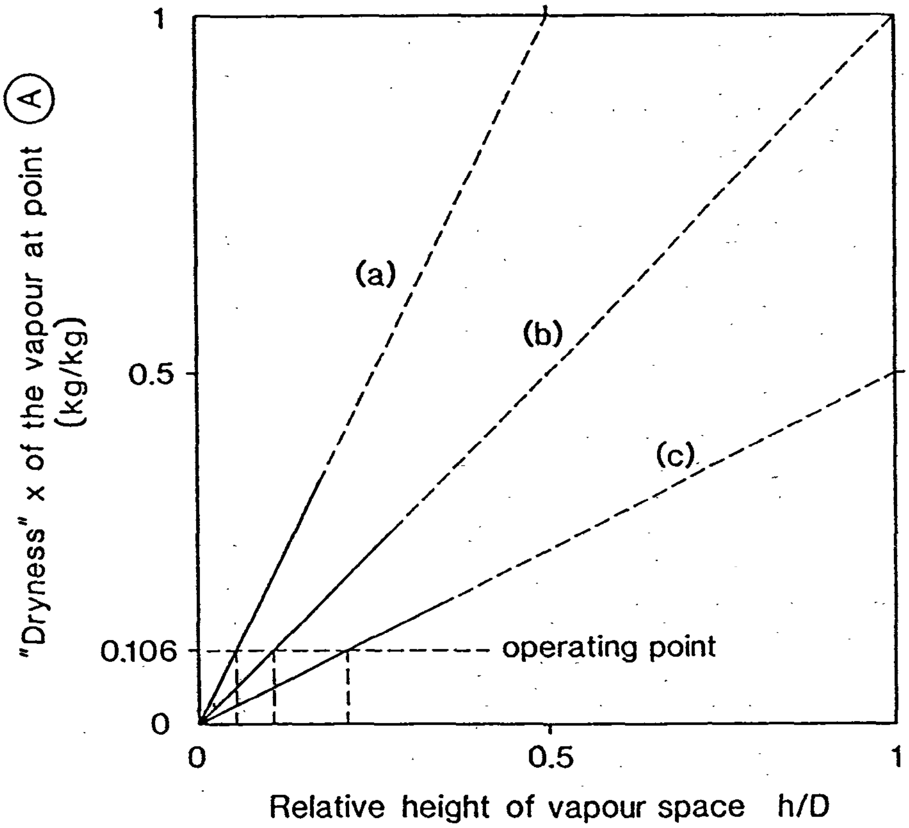

Fig. 4 Assumed relations between vapour fraction x (kg vapour per kg medium) at the level point A in Fig. 3 and relative height of the vapour space h/D in the moderator vessel. The calculated operating point to remove 3 kW of heat is at x = 10.6 %, resulting in different degrees of filling of the moderator vessel.

Of course, only the initial slope of these curves is of real importance. Table 2 gives the "arbitrary" set of starting parameters chosen at the beginning and their values 20, 30 and 60 seconds after the system was allowed to adjust to a heat input of 3 kW to the moderator vessel. While equilibrium has not yet been reached after 30 seconds in cases (a) and (c), case (b) virtually reaches its stationary situation after about 20 seconds. This is, of course, merely a consequence of the particular choice of starting parameters. After 60 seconds equilibrium has practically been reached in all cases. The fact that there exists an apparent slight difference between forward and return mass flow even after 60 seconds is a computational artifact since the calculated mass flow depends very critically on the pressure difference between the moderator and phase separator vessel. As expected, the relative filling height reached in the equilibrium situation is different for the three cases and is determined by the amount of vapour required to remove all the heat from the moderator vessel. This can be seen to be ≈ 10.6 % mass ratio in the return pipe for all cases. The filling height is important for neutronic reasons because of the effective field of view of the neutron guides.

Since the geometry is such that a loss of illumination would occur for $(1- {}^{h}/_{D}) < 0.75$, a minimum value $(1- {}^{h}/_{D}) \approx 0.8$ is desirable. This is true even in case (c) which is certainly an overly pessimistic one. An initial slope between cases (a) and (b), a situation likely to prevail in the real situation, will safely meet this condition.

The variation of $(1- {}^{h}/_{D})$ is shown for the three cases during the first 30 seconds in Fig. 5, while Fig. 6 shows the vapour content (by mass) in the return flowing liquid-gas mixture for the same time period. Although almost 90 % of the total mass leaving the moderator vessel is liquid, the vapour makes up 84 % of the volume in the pipe. The liquid does not contribute to heat transport and thus constitutes a reserve for more power to be removed from the moderator vessel. By comparing Figs. 5 and 6 it is also obvious, that, as the D_2-levels go to different equilibrium values in the three cases, the vapour fractions, after an initial "overshoot", tend towards the same mass ratio, which is achieved rather quickly in case b. The "stationary" operating point has been marked in Fig. 4 and is at 10.6 % vapour content in all cases. (Note that the "dryness" is in mass fraction, rather than volume fraction as mentioned above!)

From these results it can be concluded that safe and stable operation of the source will be possible at the anticipated power input of around 2 kW and with a large operational safety margin. Further detailed investigations of operational transients are planned for the future.

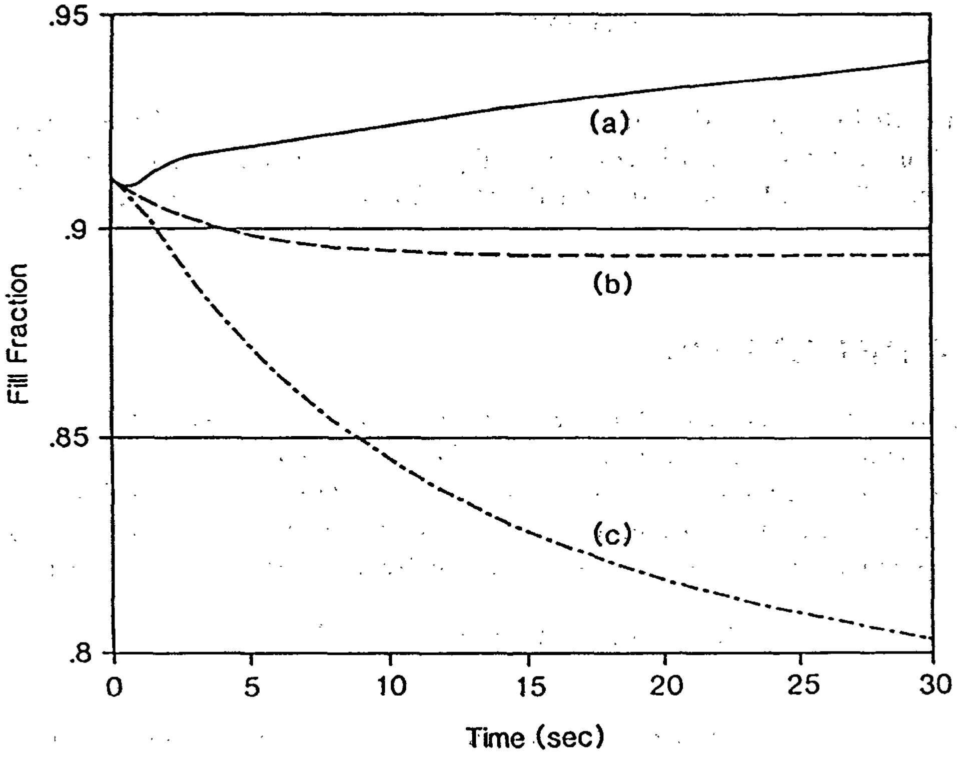

Fig. 5 Calculated filling height of the moderator vessel as a function of time for the three relations given in Fig. 4. Curve numbers (a) through (c) match in both figures. Fill fraction is (1- h/D).

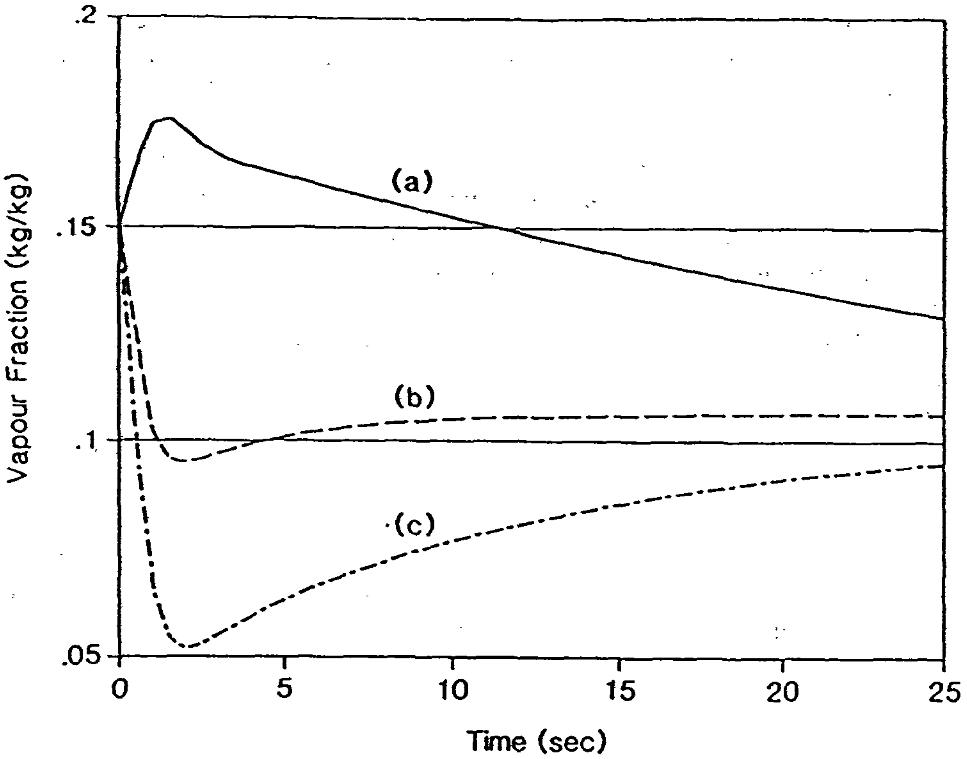

Fig. 6 Calculated change of the vapour fraction x as a function of time for the three relations between x and h/D given in Fig. 4. Curve numbers match in both figures. The equilibrium value for the three curves is x = 10.6 (kg/kg).

V SAFETY PROBLEMS

Since thermal insulation of the cold D_2-system is achieved by a vacuum environment, loss of insulating vacuum is one of the main incidents which have to be taken into account in the design. Although in general there will be a gradual increase in pressure and hence in heat transport to the cold system, it is difficult to predict exactly what sequence of events one has to consider. As a relatively flexible approximation, we assumed an exponential increase of heat transport according to the equation

$$P\,(t) \;=\; P_{max.} \cdot (1 \;-\; exp\,(-\;t/\tau)). \tag{1}$$

The time constant τ can be varied and the heat influx applied to any part of the system. τ is essentially determined by the thermal transport properties of the gas between the two walls. Heat conduction within the walls is much faster and has been neglected. The maximum power, P_{max} takes into account the variation in temperature and heat transfer coefficient in those regions, where superheated vapour is present, i.e. as the temperatures rise above the boiling point of the liquid.

The parameters chosen for the calculation are τ = 300 msec with a peak specific heat influx per unit area of 36 kW/m^2. Furthermore, in order to remain on the pessimistic side, it was assumed, that, at the moment of loss of vacuum, the moderator vessel was filled to the level of the outlet pipe and the connecting pipes to the phase separator were completely filled with stationary liquid (no circulation). The phase separator was assumed to be 10 % full, as given by the total amount of D_2 in the system.

The increase of heat input to the moderator vessel as a function of time is shown in Fig. 7 for the first one second; Fig. 8 gives the pressure in the moderator vessel and the phase separator for the same period of time. It can be seen that, as a consequence of the expulsion of the liquid from the pipe system, a temporary increase in pressure from the stationary value of 1.56 bars to 2.25 bars takes place, which decreases again, as more and more D_2 is expelled from the moderator vessel.

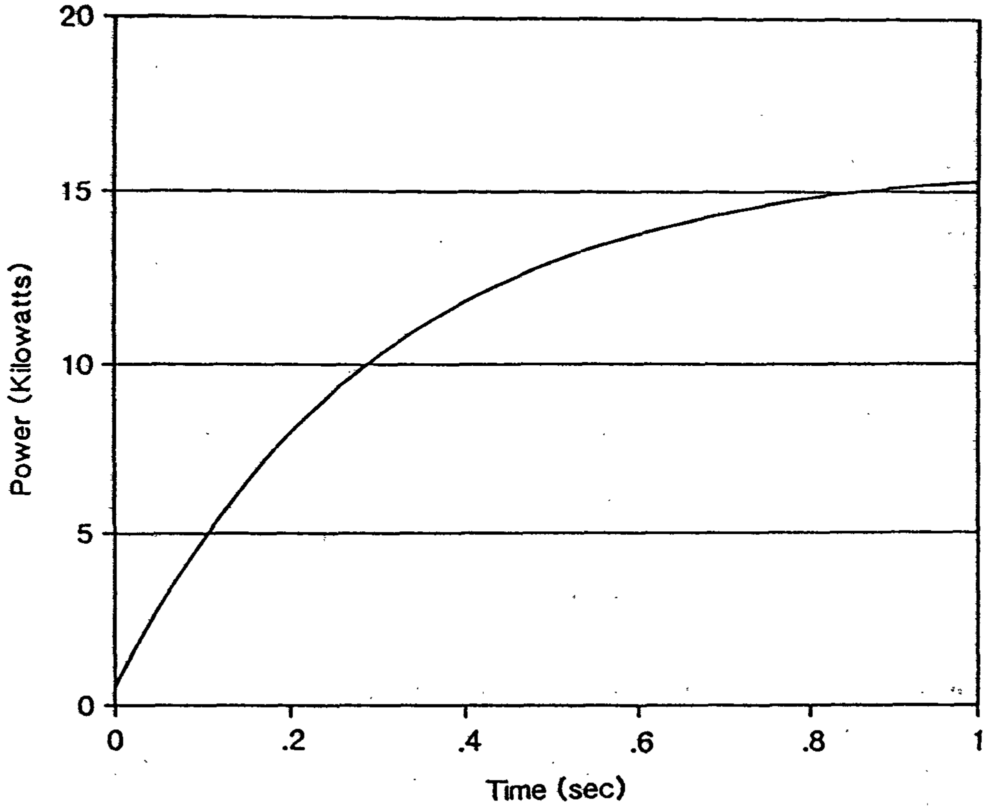

Fig. 7 Assumed variation of power input to the moderator vessel after a loss of insulating vacuum at t = 0. At t< 0 the system was in a steady state with only 0.5 kW of power input (thermal losses) and virtually no D_2- circulation.

The flow velocity of the medium at various points in the system as a function of time is shown in Fig. 9. As a consequence of the simultaneous onset of heat influx on all cold parts of the system, flow starts at t = 0 everywhere in the cold part with a delay due to the velocity of sound at the entrance to the ballast tank (curve d). The various "capacitor" volumes are also visible at that point. Furthermore, it can be observed that, at very short times, a return flow exists from segment 1 to the moderator vessel which results from the compressibility of the vapour initially present in the moderator vessel.

Taking into account that the gas pressure in the system is 2.8 bars when warm, the results found here give no cause for concern. (The system pressure of 2.8 bars will eventually be reached at long times, but 1 sec is by far, too short to notice any move in that direction).

As a consequence of the rapid expulsion of the cold medium from the moderator vessel and the phase separator, a front of cold medium is pushed through the pipe connecting the phase separator to the ballast tank. Assuming that, at stationary state, a linear temperature gradient exists over the length of pipe segment 3 between 25 K and 298 K the change in temperature at various points of the system is shown in Fig. 10. The onset of the temperature drop is linked to mass transport rather than to the velocity of sound as is the onset of mass flow. Hence the longer delay.

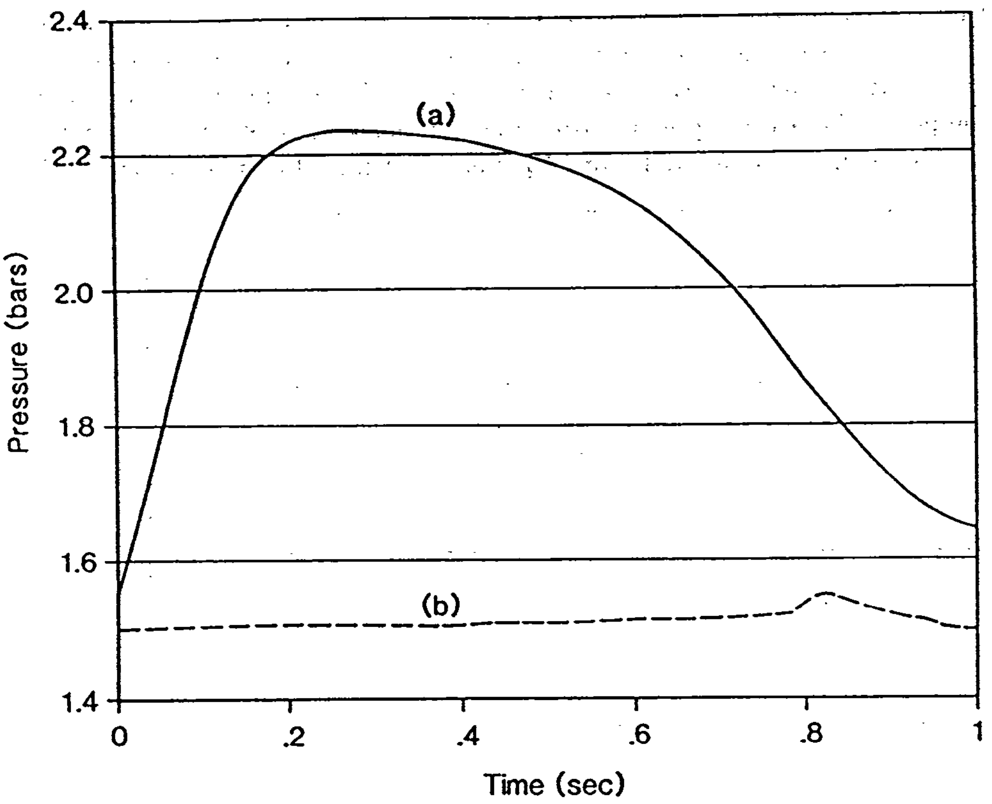

Fig. 8 Pressure in the moderator vessel (curve a) and in the phase separator (curve b) during the first one second after a loss of insulating vacuum. At longer times the pressure increases very gently as the liquid evaporates and the system warms up.

The effect of heat input to the pipe is clearly visible as a change in slope as the cold front propagates along the pipe.

It is important to note that the whole length of the transfer pipe between phase separator and ballast tank will be cooled down to 25 K in the case of a loss of insulating vacuum. (This has to be accounted for in the layout of the pipe.)

The above results are also applicable to the situation of a fairly sudden rupture of the moderator vessel with D_2-spill into the vacuum space, as long as the return flow pipe to the phase separator remains unblocked. The extra volume available in this case will even help to keep the pressure on the vacuum jacket lower. This situation remains to be considered in more detail.

For the sake of completeness, although of no real meaning, two increasingly simplified cases have also been considered:

- all heat input goes to the moderator and phase separator volumes alone, (no heating of the connecting pipes);
- as before, but in addition an effecting instantaneous increase of heat input to its maximum value (τ = 3 ms)

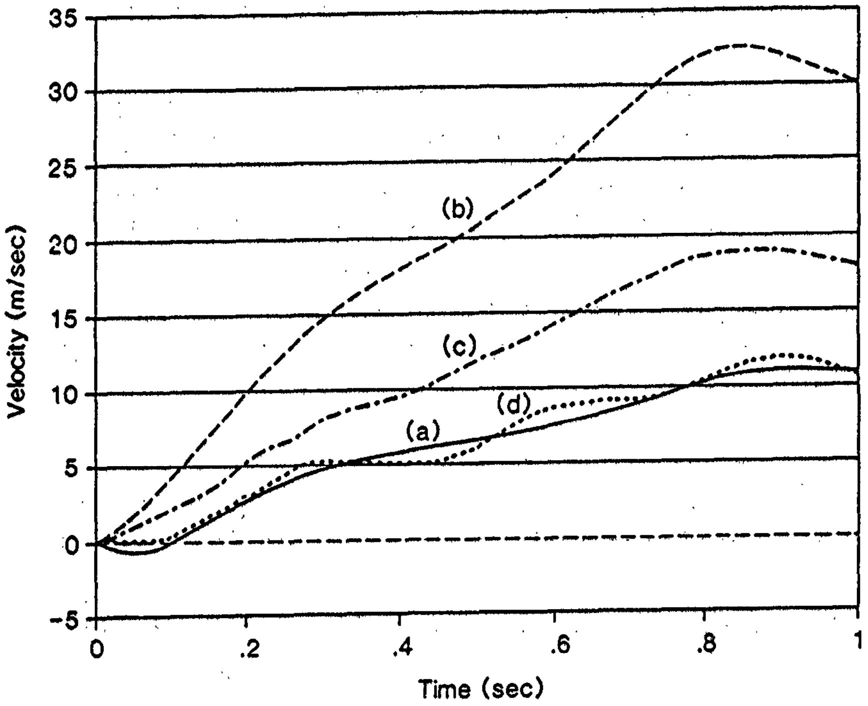

Fig. 9 Flow velocity at various points in the D_2-system after a loss of insulating vacuum at t = 0.
curve (a) : point 1 in Fig. 2 (exit of moderator vessel)
curve (b) : point 3 in Fig. 2 (entrance to phase separator)
curve (c) : point 4 in Fig. 2 (exit of phase separator)
curve (d) : point 8 in Fig. 2 (entrance of D_2-ballast tank)

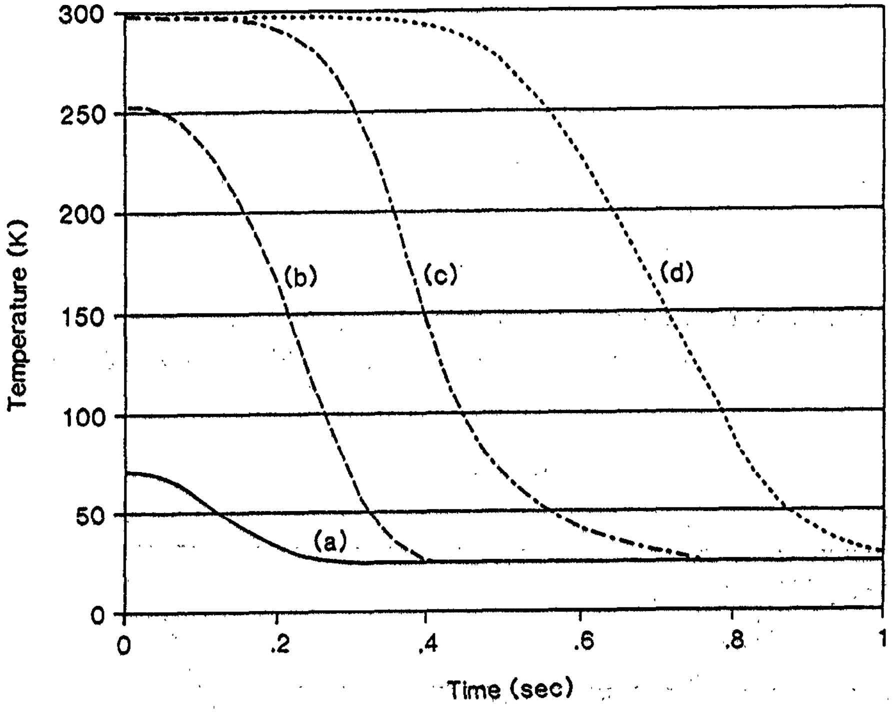

Fig. 10 Temperature evolution at various points in the D_2-system after a loss of insulating vacuum at t = 0.
(a) point 5 in Fig. 2 (at 30 cm above heat exchanger vessel)
(b) point 6 in Fig. 2 (at 150 cm above heat exchanger vessel)
(c) point 7 in Fig. 2 (at 180 cm above heat exchange vessel)
(d) point 8 in Fig. 2 (entrance to D_2-ballast tank)

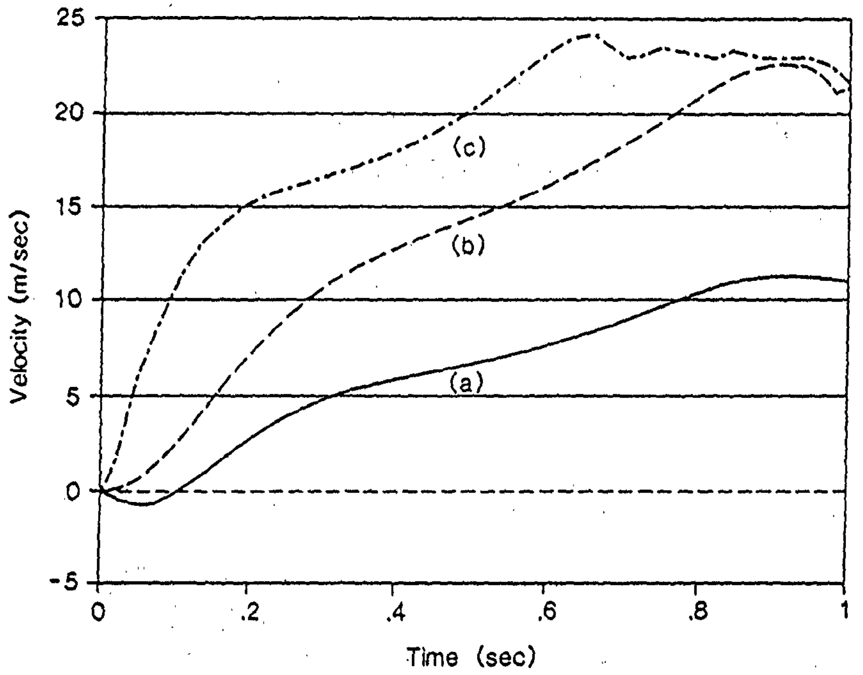

Fig. 11 Flow velocity of medium at the exit point from the moderator vessel (point 1 in Fig. 2) for three different assumptions on heat input
(a) heat input along the whole D_2-system according to Figure 7 with 3.6 W/cm^2 of surface, heat flux
(b) Heat input concentrated on moderator and phase separator volumes but matching the total heat input of curve (a).
(c) as b but time constant of power rise reduced from 300 ms to 3 ms.

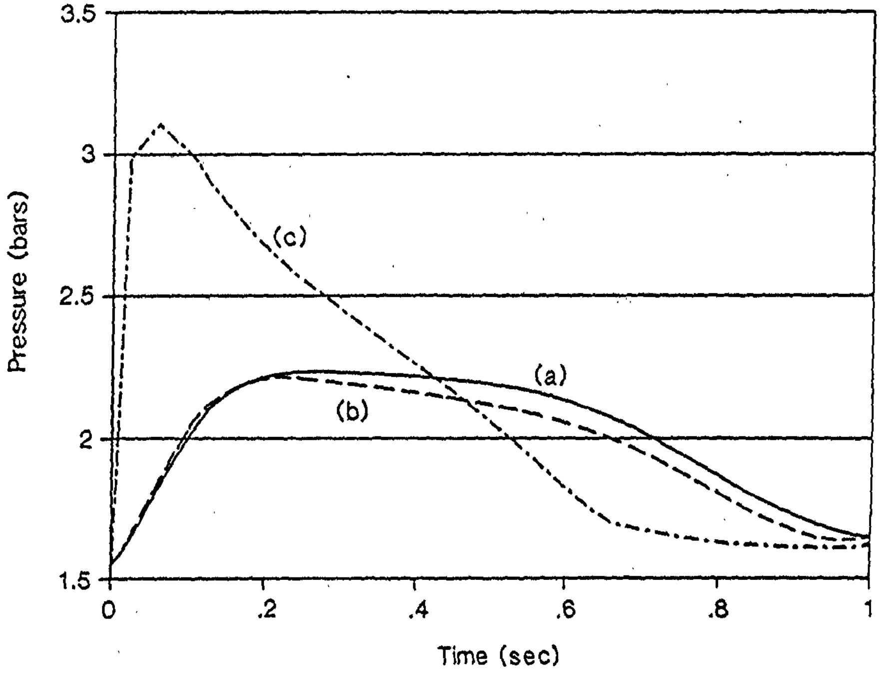

Fig. 12 Pressure rise in the moderator vessel for the three cases of Fig. 11. Curve numbers in both figures match.

The flow velocities at the entrance to pipe segment A are shown in Fig. 11 for the three cases. It can be seen that "backfiring" only occurs when heat input to the pipe is allowed. As expected, a much faster velocity results from the increased heat input, with a clearly visible faster rise in the step function case.

Nevertheless, as can be seen from Fig. 12, where the resulting pressure increase in the moderator vessel is shown, no dangerous situation with respect to the integrity of the moderator vessel will be encountered, even under the assumption of an "instantaneous" rise of the heat input (curve c). From curve a and b it can be seen that the lack of "backfiring" into the moderator vessel in case b results in a lower peak value and a faster decrease of the pressure although the total heat to the moderator vessel input is higher than in case a.

VI CONCLUSIONS

The computational model set up for the D_2-system of the SINQ cold moderator helped us to understand and predict very well the behaviour of the system under normal operating conditions as well as in the incident of a loss of insulating vacuum. It could be shown that the design pressure of the moderator vessel is not reached or exceeded in any situation, even under non-realistic assumptions. The model will be used in future to further refine our understanding of the behaviour and - if required - to study other accident scenarios.

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