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*) Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung mbH.,Karlsruhe

SODIUM BOILING AND FAST REACTOR SAFETY *)

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ABSTRACT

For fast sodium cooled reactor safety analysis liquid metal superheat and coolant flashing is very important. Investigation of the ejection mechanism with the digital code BLOW shows good agreement with experimental results. Present knowledge on sodium superheat is reviewed and discussed in some detail, especially to demonstrate the great differences in experimental data, and from this a research program is established. Also recondensation effects with their high pressure peaks are investigated, theoretical and experimental results are presented.

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*) Work performed within the framework of the association Euratom - Gesellschaft für Kernforschung mbH. in the field of fast breeder development.

1. INTRODUCTION

The existence of a positive coolant void coefficient of large fast reactors has resulted in an intensification of research on liquid metal boiling. Even though the probability of coolant boiling in a sodium cooled fast reactor is very low, the consequences of such an incident may lead to a serious destruction of the core. Therefore, a good understanding of the boiling mechanism is required for safety reasons. It is the purpose of this paper to give a review of the present status of knowledge and to outline the work underway within the German fast breeder program. We shall concentrate here on the principal aspects, whereas the practical application to the design of the German 300 MWe prototype reactor has been described in another contribution to this conference [1].

From the standpoint of fast reactor safety there are 3 questions which must be answered on the basis of a good understanding of the mechanisms involved:

a) How fast will the coolant be ejected from a single coolant channel or a subassembly?

b) What degree of liquid superheat will be reached?

c) How will vapor-recondensation or bubble-collapsing take place?

To understand the relative importance on reactor safety of the answers to questions a) - c) we consider the chains of events as shown in fig. 1.

First we note that overall sodium boiling requires always besides the primary disturbance the occurence of a simultaneous failure of the safety system as a second condition. As we have shown previously [2] a conventional safety system is well capable to control accidental reactivity insertions well before the sodium would reach the boiling point. The same is true for loss of coolant flow incidents. If a single channel is blocked, local boiling may occur. But only if this incident is not detected and no protective actions are taken the boiling may spread over a larger portion of the core. Then finally in all these cases the coolant will be ejected and a steep reactivity increase as a secondary disturbance would lead to

disassembly of the core [1]. The maximum void reactivity normally amounts up to several Dollars. However, we have to consider only the voiding up to about 1.5 $, since then the disassembly feedback on reactivity will rapidly shut the reactor down. Thus, both the axial coolant ejection and the radial propagation of this phenomenon determine the rate of reactivity insertion. The answer to question a) provides the first step in this analysis.

As will be shown below, the ejection time from a channel depends strongly on the amount of liquid superheat, and this leads to question b). Also the time sequence in which the ejection takes place from different channels depends on the amount of superheat as well as on how desuperheating is initiated. For an equal amount of superheat in each channel this time sequence will follow the pattern of the power profile. However, it cannot be ruled out so far that the ejection from one channel might trigger the superheated neighbour channels by a pressure wave, which would increase the rate of radial void growth. Analysis of this problem is the second step in the calculation of the steepness of the secondary disturbance. Since the first step, the ejection from the single channel, is very rapid, the rate of reactivity increase depends mainly on the second step as the time determining factor, the spread-out of the ejection to the other channels. This again underlines the importance of superheat and superheat release.

Whereas the pressure shocks by flashing in a superheated liquid are determined by the corresponding saturated vapor pressure and are, therefore, limited, the pressure peaks by recondensation, i.e. by the impact of a collapsing bubble, may be very high and much more destructive to the core. Therefore, before ruling out the possibility of propagative fuel element destruction one must have an answer to question c). We shall now discuss the three questions in the given sequence.

2. SINGLE CHANNEL EJECTION

To our opinion the mechanism of the single channel ejection is understood quite well by now. Starting from the experience with water [3] several authors have developed theoretical models on the basis that an intimate

mixture of liquid and vapor is being ejected. We mention the code TRANSFUGUE of R.C.Noyes [4] and the work of Mac Farlane [5]. Fischer and Häfele [6] were successful in solving the numerical stability problems of such calculations by application of the characteristics-method to the equations of the two-phase-mixture.

However, the experimental evidence shows that for sodium these two-phase models do not apply. As shown by Noyes [7] and by Grass [8] the liquid metal is expelled by the expansion of one single vapor bubble. Therefore, "piston-type" ejection models are more correct. The first codes on this basis were VOID of General Electric [9] and BURP of Atomics International [7]. Whereas VOID uses an empirical relationship of the internal bubble pressure as a function of the channel wall temperature, BURP assumes, that liquid is evaporated only from the liquid-vapor-interface at both ends of the bubble.

The results of experiments done in cooperation with the Karlsruhe Project at Ispra with K [10] and experiments of Schultheiss at Karlsruhe (unpublished) have shown the existence of a thin liquid layer on the heated surface during the bubble growth. The same type of liquid layer also has been observed in experiments on the sodium-water-reaction [11], where sodium is expelled by basically the same mechanism.

Fig. 2 shows for example a typical result of the Karlsruhe experiments. In this case the liquid metal has been simulated by ethanol. By application of low pressure it has been possible to obtain similar liquid-vapor density ratios as for Na and also some superheat. A single bubble evolved at a predetermined site. By the difference in light reflection the liquid layer on the heater rod can be seen inside the bubble, when finally after some 10 milliseconds a dry spot develops and spreads over the heater.

Evaporation of this liquid layer determines heavily the velocity of bubble growth. Based upon the evidence of this and other experiments [10,11] the code BLOW has been developed by Schlechtendahl [12].

In the following we will give a brief description of the theoretical model which is being used in this code. There is no need to describe the equations of heat conduction in the fuel pin and the cladding because they

are well known. Also the ejection process does not involve any sophistication since it is simply described by Newton's law. However, it ought to be noted that the inertia and the friction of the liquid coolant must be taken into account, not only within the coolant channel but also along the whole flow path of the reactor coolant system until a free surface is reached. Otherwise the velocity of the coolant ejection would be markedly overestimated.

Here we will concentrate on the boiling process which supplies vapor to the expanding bubble from the liquid surface layer. Fig. 2 shows a schematic drawing of this layer. It is assumed that this liquid layer is not in thermodynamic equilibrium with the gas bubble, but that there is an exchange of mass and energy between the layer and the bubble. An estimate of this mass and energy transport can be made if one considers the streams of condensating and evaporating material separately.
It is assumed that all material which enters the vapor bubble from the liquid layer originally was in equilibrium with this layer and that the vapor stream which condensates on the surface of the layer originally was in equilibrium with the vapor bubble. From a momentum balance one obtains readily the equations

$$\mu_B \cdot u_B = p_B$$
$$\mu_L \cdot u_L = p_L$$

with:

μ_B = mass flow density of condensating atoms
μ_L = mass flow density of evaporating atoms
u_B = mean velocity of condensating atoms
u_L = mean velocity of evaporating atoms
p = pressure
subscript B means bubble
subscript L means layer

Applying the kinetic theory of gases to this model the mean atom velocities can be calculated as a function of the state variables of the bubble and the layer:

$$u_B = \sqrt{\frac{8}{\pi} R T_B}$$

$$u_L = \sqrt{\frac{8}{\pi} R T_L}$$

with

T = temperature

R = gas constant

Thus the net mass flow density μ is given by

$$\mu = \mu_L - \mu_V = \frac{p_L}{\sqrt{\frac{8}{\pi} R T_L}} - \frac{p_B}{\sqrt{\frac{8}{\pi} R T_B}}$$

Together with the mass exchange between layer and bubble also energy is exchanged between the two. If h_B is the enthalpy of the vapor in the bubble and h_L is the enthalpy of saturated vapor at the layer temperature the net energy flow density e is given by

$$e = \mu_L \cdot h_L - \mu_B \cdot h_B = \frac{p_L \cdot h_L}{\sqrt{\frac{8}{\pi} R T_L}} - \frac{p_B \cdot h_B}{\sqrt{\frac{8}{\pi} R T_B}}$$

With these equations the mass and energy transfer of the transient evaporation process are fully described. However, it can be demonstrated that for typical fast reactor core geometries the bubble and the liquid layer come into thermodynamic equilibrium within a few microseconds. An order of magnitude estimate of the time constant τ of this process can be drawn from a linearized version of the mass and energy balance for the vapor in the bubble and is given by

$$\tau = \frac{2}{\pi} \cdot \frac{D_H}{\sqrt{\frac{8}{\pi} R T_L}}$$

with D_H being the hydraulic diameter of the bubble. Remembering that $\sqrt{\frac{8}{\pi} R T_L}$ is the mean velocity of the vapor atoms, this time constant is roughly equal to the travel time of the vapor atoms through the bubble. For a typical core geometry of a sodium cooled reactor [1] one obtains

$$\tau = 4 \cdot 10^{-6} \text{ sec.}$$

Hence, it is well justified to neglect the transient phenomena of the boiling process. Yet, it is not justified to neglect the feedback of the boiling process upon the liquid layer completely, since this would mean that the two effects

dryout of the layer and
cooling by vaporization

would be neglected. However, this feedback can be computed easily if one calculates the net mass and energy streams μ and e from the time differential of the mass and energy of the vapor in the bubble. This procedure is analogous to the socalled prompt jump approximation frequently used in the solution of the reactor kinetics equations. In order to test the computational model, the BLOW-code was used to simulate potassium-ejection experiments performed at Ispra. A detailed description of these experiments is given in ref. [8]. Curves 1 and 2 of the figures 3a through 3c are taken from the reference while curves 3 and 4 represent the numerical results of the calculation. It was found necessary to match liquid superheat such as to get the measured ejection behaviour. In fig. 3a stagnant potassium is ejected with 95°C superheat. Fig. 3b shows ejection starting from natural convection with 65°C superheat (measured:29°C). In fig. 3c the ejection starts from forced convection with 25°C superheat (measured: 11°C). Because of the difficulty of measuring the exact temperature at the point of bubble nucleation the discrepancy between the measured and the assumed superheat temperature is not too difficult to explain. Although there is a slight parallel displacement of the calculated total bubble length as compared to the reference, the ejection process is well represented in all cases. The application of the theoretical model to reactor accident analyses appears to be justified.

Figures 4a and 4b show results of numerical calculations of various coolant ejection processes. In all cases a geometry typical of a 300 MWe sodium cooled reactor was used. It was also assumed that the coolant was stagnant prior to the initial bubble formation. The pressure in the reactor coolant system was 1 at. The first bubble formation was assumed

to occur at the temperature T_{Na} while the fuel was at a temperature T_f. From the figure it can be seen that at high superheat the ejection process is determined by the degree of superheat only and the heat flux from the fuel to the sodium is of no importance. At low superheat (less than 100°C above normal boiling point) the heat flux from the fuel becomes rather important. It is, therefore, essential to know what degree of superheat we must expect in a sodium cooled reactor, not only because this is in itself an important parameter which determines the initial pressure in the bubble, but also because future reactor accident analysis will depend on whether the heat flux is important or not. In any case future theoretical analysis of sodium ejection incidents in sodium cooled reactors will have to concentrate on the following:

a) the early phases of bubble formation until the whole cross section of the fuel assembly is voided over some length,

b) the influence of axial differences in fuel, clad and sodium temperature upon the ejection process,

c) the radial propagation of the incident.

3. SODIUM SUPERHEAT

There is still considerable lack of knowledge regarding alkali metal superheat. The published experiments on Na and K show a wide range of measured wall superheats. For pool boiling of Na values of 20°C [13,14] up to about 100°C [15,16], for NaK nearly 160°C [17] have been reported. In a natural convection loop K shows up to 330°C [18]. Under forced convection the same researchers have got 160°C to 220°C [18,19]. For stagnant K under very clean conditions the Ispra group has found maximum values up to 800°C [10], whereas in a forced circulation loop, probably under less clean conditions only about 50°C have been observed [10]. With the exception of the experiment with stagnant K [10] the purity of the liquid metal and the amount of dissolved gases is not very well known. The experimental data available to date are not very conclusive, However, with some caution it can be expected, that under reactor conditions the superheat will probably not exceed some 10°C. Especially with free-surface

pumps there will be some carry-under of cover-gas and even very tiny gas-bubbles may exist in the coolant, which can act as active nuclei. But the final proof is still missing.

The conditions of the heated wall are of particular importance. Starting from the wellknown condition

$$\Delta t = t_w - t_{sat} = \frac{2\,\sigma\, t_{sat}}{h_v\, \varrho_v\, r} \cos\theta$$

we have the dependence of the superheat Δt on the surface tension σ, the saturation temperature t_{sat}, the heat of vaporization h_v, the vapor density ϱ_v, the radius of the nucleus r and the contact angle θ.
In all used models for bubble nucleation the nucleus must exist in the form of a gas or vapor bubble. In the case of ordinary liquids the surface cavities normally contain enough nuclei in form of adsorbed or enclosed gas. These cavities are called "active sites" for bubble generation. In the case of sodium a nucleus of radius r results in a higher superheat as compared for example to water since σ and t_{sat} are higher and ϱ_v is lower for Na than for H_2O at the same pressure.
But the main problem is that sodium at more than 300°C is a very wetting liquid with a contact angle of almost zero. Therefore, eventually liquid Na will fill all cavities entirely and make them inactive. Marto and Rohsenow [16,20], Shai [21] and Petukhov et al [13] have considered the stability of a nucleation site. They developed a criterion under which conditions a vapor bubble at the bottom of a cylindrical cavity will condensate or not. For sodium the stability of the active site is very poor. This results from the small θ, the high t_{sat} (instability $\sim t_{sat}^2$ [21]), the high thermal conductivity and the low vapor density. The measurements of Petukhov et al.[13] and Shai [21] gave a rough qualitative, but no quantitative agreement with this simplified theory. It can be concluded from this work [21] that conical cavities probably cannot be active at all, cylindrical cavities have a critical heat flux above which stable boiling exists, but which would be very high for alkali metals, and the so-called "re-entry cavities", as sketched in fig. 5, are the most stable ones at low heat fluxes too. Here the radius of curvature of the sodium-vapor interface must pass infinity as the liquid enters the cavity. As Petukhov[13] points out for $\theta = 0$ only such a cavity can stay active. In none of these

experiments the chemical composition of the sodium or the amount of dissolved gases has been measured.

It must be pointed out that the main concern of this work has been the boiling heat transfer and especially boiling stability. Therefore, the authors studied boiling nuclei consisting of vapor, not of gas.

In the fast reactor safety one encounters quite a different problem. Here the coolant has been passing the heated surfaces in the liquid phase for a very long time in the order of years. During this time the sodium has cleaned the surface to a very large degree. It is not very probable that any gas bubbles have been left even in re-entry cavities. So besides of the conditions of the cavities the impurities and dissolved gases in the liquid metal probably are even more important than in the case when boiling already has started and the stability of vapor nuclei is the main concern.

Therefore, the knowledge of the solubility of inert gases, especially Helium and Argon, in liquid sodium is required. The presently known measurements are limited to temperatures below 600°C (22,23,24,25) and show an increasing solubility with temperature.

Starting from this reasoning we have established the following research program on sodium superheat:

a) Measurement of solubility of Helium and Argon in Sodium up to boiling temperature.

b) Pool experiments under controlled Sodium conditions on first nucleation at artificial cavities, development of methods for the direct observation of bubbles. Comparison and classification of technical surfaces.

c) Loop experiments under controlled Sodium conditions with special emphasis on the wall effects. The general arrangement of the loop is shown in fig. 6. The stainless-steel test section A - B is heated by an oil cooled high-frequency power supply, which permits heat fluxes up to 500 W/cm^2. The whole equipment is arranged inside a containment in nitrogen atmosphere because of higher security in case of an accident.

d) All described experiments can be connected to a sodium facility with an inventory of several tons of sodium and complete purification equipment for sodium and cover gas. By this, constant conditions, clean conditions and reactor conditions can be verified.

e) Whereas the Karlsruhe work is mainly concentrated on the influence of wall effects on superheat, the Ispra Heat Transfer Laboratory in a coordinated effort to a great deal is concerned with nucleation in the liquid metal itself, especially on the behaviour of inert gas bubbles.

4. RECONDENSATION

As many others we have observed pressure peaks during sodium pool boiling, much larger than to be expected from the observed superheat and corresponding saturated vapor pressure. It is generally agreed that these peaks are caused by collapsing bubbles.

The behaviour of a special bubble in an infinite liquid medium is described by (26)

$$r \frac{d^2r}{dt^2} = \frac{p_B - p_\infty}{\varrho} - 1.5 \left(\frac{dr}{dt}\right)^2$$

where p_B is the pressure in the bubble, p_∞ the pressure far away from the bubble, ϱ the liquid density and r the bubble radius. One can assume that the vapor pressure in the bubble has become equal to the saturation pressure of the surrounding liquid. If this is less than p_∞ the bubble will collapse. As a first approach we assumed that the residual vapor in the bubble is compressed adiabatically, and behaves as an ideal gas. Fig. 7a shows the pressure pulses calculated with this model for collapse of bubble of 1 mm radius in a sodium pool of 500°C and 0.26 at pressure. Peak pressure pulses up to 50 atm at a period of 300 microseconds were calculated, while the bubble radius oscillates between 1 mm and 0.15 mm, as fig. 7b shows. It is realized that these oscillations will be damped out rapidly by further condensation and heat losses into the liquid. A blocked channel simulating experiment of W.Peppler in Karlsruhe (unpublished) indicates that these theoretical predictions give a good understanding of the ejection-bubble behaviour, although they are strongly idealized and don't consider any vapor condensation.
Fig. 8 shows the experimental results in a pressure and temperature versus

time diagram. It should be emphasized that the high pressure pulses which occur during condensation last only for a few microseconds, and they decrease rapidly with the distance from the bubble. In the above example only about 1 at peak pressure would be noticed at a 1 cm distance. Further research work on this subject will have to take into account transient heat conduction and phase change processes as well as shock wave phenomena. Analysis of the potential damage which they may cause must, therefore, take into account the dynamic response of the core structure.

The kinetic energy of liquid sodium flowing back into a voided fuel element may be used as an estimate for the potential structure deformation. Preliminary analysis indicates that the sodium columns might reach a velocity of 10 to 20 m/sec. In a typical 300 MWe reactor geometry this would correspond to about 500 to 2000 Wsec of kinetic energy. If all of this energy would have to be absorbed by the fuel element wrapper tube, significant local deformation would have to be expected, especially if the structure has been heated up to the sodium boiling temperature where it would lose almost all strength. Until now, the supporting effect of the surrounding fuel elements has been neglected. This apparently is a too pessimistic assumption. It is believed that in the actual core arrangement a considerable number of boiling and recondensation cycles may be sustained before the deformation of the surrounding fuel elements is sufficient for failure propagation. Although this would not eliminate the problem, more time to take corrective actions would be gained.

Naturally these calculations are oversimplified in many respects. Contrary to ejection and superheat the actual geometry is of particular importance for the strength of recondensation shocks and the probability of damage propagation over the core. Especially it depends on the pattern of the reentry of the liquid sodium into a multirod subassembly after the first ejection. Therefore, an arrangement of a large number of heated rods under boiling sodium would be required in principle. However, such an experiment would be very difficult, very expensive and very time-consuming. It would also be nearly impossible to observe the re-entering sodium.

Therefore, for the first step we have restricted our experimental program on recondensation of sodium to a single-channel geometry.

a) Experiments will be carried out with the loop as described under 3c). The geometry of a Na-filled tube heated from the outside gives a closer approach to reality than a single heated rod in an annular channel.

b) Experiments have started with a similar geometry as under a) with water. By operating at low pressure and keeping the water clean it is possible to obtain conditions comparable to sodium and especially a considerable superheat.

c) A multirod geometry will be used with water. With the information and comparison of a) and b) it is hoped to be able to draw some conclusion on the behaviour of sodium in a real subassembly.

5. CONCLUSIONS

a) Sodium boiling can start or can be dangerous for the whole core only in case of a malfunction of the safety system. Improvement of the safety system reliability to prevent boiling is, therefore, a most important target in fast sodium cooled reactor development.

b) The least improbable event is boiling in a single subassembly. Since boiling detection equipment is still under development, the impossibility of damage propagation should be assured by experiment.

c) Propagation may be triggered by superheat, more probably by recondensation shocks. It is hoped to exclude both possibilities by the described experiments and by proper design of the fuel subassembly.

d) The mechanism of single channel ejection is understood quite well. It depends on superheat, as also does the velocity of spread out over other channels.

e) Superheat and nucleation are not yet understood. A research program is underway, where well defined conditions of the liquid metal and the wall are the main requirements.

REFERENCES

(1) E.G.Schlechtendahl et al.: Safety features of a 300 MWe sodium cooled fast breeder reactor (Na 2). Paper presented at this conference.

(2) D.Smidt et al.: Systemanalyse eines 1000 MWe natriumgekühlten schnellen Leistungsreaktors, Ext.Bericht 8/66-6, December 1966, ANL-7120

(3) A.M.Judd: Loss-of-coolant accidents in a large sodium-cooled fast reactor. ANL-7120, October 1965

(4) R.C.Noyes, J.G.Morgan, H.H.Cappel: TRANSFUGUE-I, a digital code for transient two-phase flow and heat transfer. NAA-SR-11008, July 1965

(5) D.R.Mac Farlane: An analytic study of the transient boiling of sodium in reactor coolant channels. ANL-7222, June 1966

(6) M.Fischer, W.Häfele: Shock front conditions in two phase flow including the case of desuperheat. ANL-7120, October 1965

M.Fischer, W.Häfele: Occurrence of shock waves in two phase flow. Symposium on Two-Phase Flow Dynamics, Eindhoven, Sept.1967

(7) R.C.Noyes, H.Lurie, A.A.Jarrett: The development and growth of in-core voids due to boiling during fast reactor transients. ANL-7120, Oct.1965

(8) G.Grass, H.Kottowski, R.Warnsing: Das Sieden von flüssigen Alkalimetallen. Zeitschrift "Atomkernenergie", 12.Jahrg.(1967), H.3/4, pp.101-110

(9) General Electric Co.: Fast ceramic reactor development program. Eighteenth Quarterly Report, GEAP-5158, April 1966

(10) K.H.Spiller, G.Grass, D.Perschke: Überhitzung und Einzelblasenejektion bei der Verdampfung von stagnierenden Flüssigmetallen. Zeitschrift "Atomkernenergie", 12.Jahrg.(1967) , H.3/4, pp.111-114

(11) K.Dumm, H.Mausbeck, W.Schnitker: Experimental and theoretical investigations of sodium-water reactions in tubes. CREST, Meeting of specialists on shock structure interactions in a reactor, Ispra, June 1966

(12) E.U.Schlechtendahl: Die Ejektion von Natrium aus Reaktorkühlkanälen. (to be published)

(13) B.S.Petukhov, S.A.Kovaler, V.M.Zhukov: Study of sodium boiling heat transfer. Proc.of 3.Int.Heat Transfer Conf., Chicago, August 1966, Vol. V, pp.80-91

(14) Private information Dounreay.

(15) R.C.Noyes: Boiling studies for sodium reactor safety, Part I. NAA-SR-7909, 1963

(16) P.J.Marto, W.M.Rohsenow: Effects of Surface conditions on nucleate pool boiling of sodium. Trans.ASME, Ser.C., Journ.Heat Transfer 88, 1966, No.2, pp.196-204

(17) N.Madsen, C.F.Bonilla: Heat transfer to sodium-potassium alloy in pool boiling. Chem.Eng.Progr.Symp., Ser.56, 1960, No.30, pp.251-259

(18) H.W.Hoffmann, A.I.Krakoviak: Convective boiling with liquid potassium. Heat Transfer and Fluid Mechanisc Institute, Univ.of California, Berkeley, 10-12 June 1964, Stanford University Press, pp.19-37

(19) H.W.Hoffmann, A.I.Krakoviak: Forced convection saturation boiling of potassium at near-atmospheric pressure. Proc.of 1962 High-Temp.Liquid Metal Heat Transfer Technology Meeting, BNL 756,1963, pp.182-203

(20) P.J.Marto, W.M.Rohsenow: The effect of surface conditions on pool boiling heat transfer of sodium. Proc. of 1963 High-Temp.Liquid Metal Heat Transfer Techn.Meeting, ORNL-3605,1964, Vol.1, pp.263-285

(21) I.Shai: The mechanism of nucleate pool boiling heat transfer to sodium on the criterion for stable boiling. MIT, Jan.1967, DSR 76303-45, Contract No. AI(30-1) 3357, A/3

(22) R.E.Holtz: The effect of the pressure-temperature history upon incipient-boiling superheats in liquid metals. ANL-7184, 1966

(23) H.Slotnick, S.M.Kapelner, R.E.Cleary: The solubility of helium in lithium and potassium. PWAC-380,1965, Contract AT(30-1)-2789

(24) S.K.Dhar: Solubility of argon in sodium. ANL-6800, pp.183-187

(25) S.K.Dhar: solubility of krypton in liquid sodium. ANL-6900, pp.125-127

(26) H.Lamb: Hydrodynamics. 6.Edition, Cambridge University Press, pp.122,1932

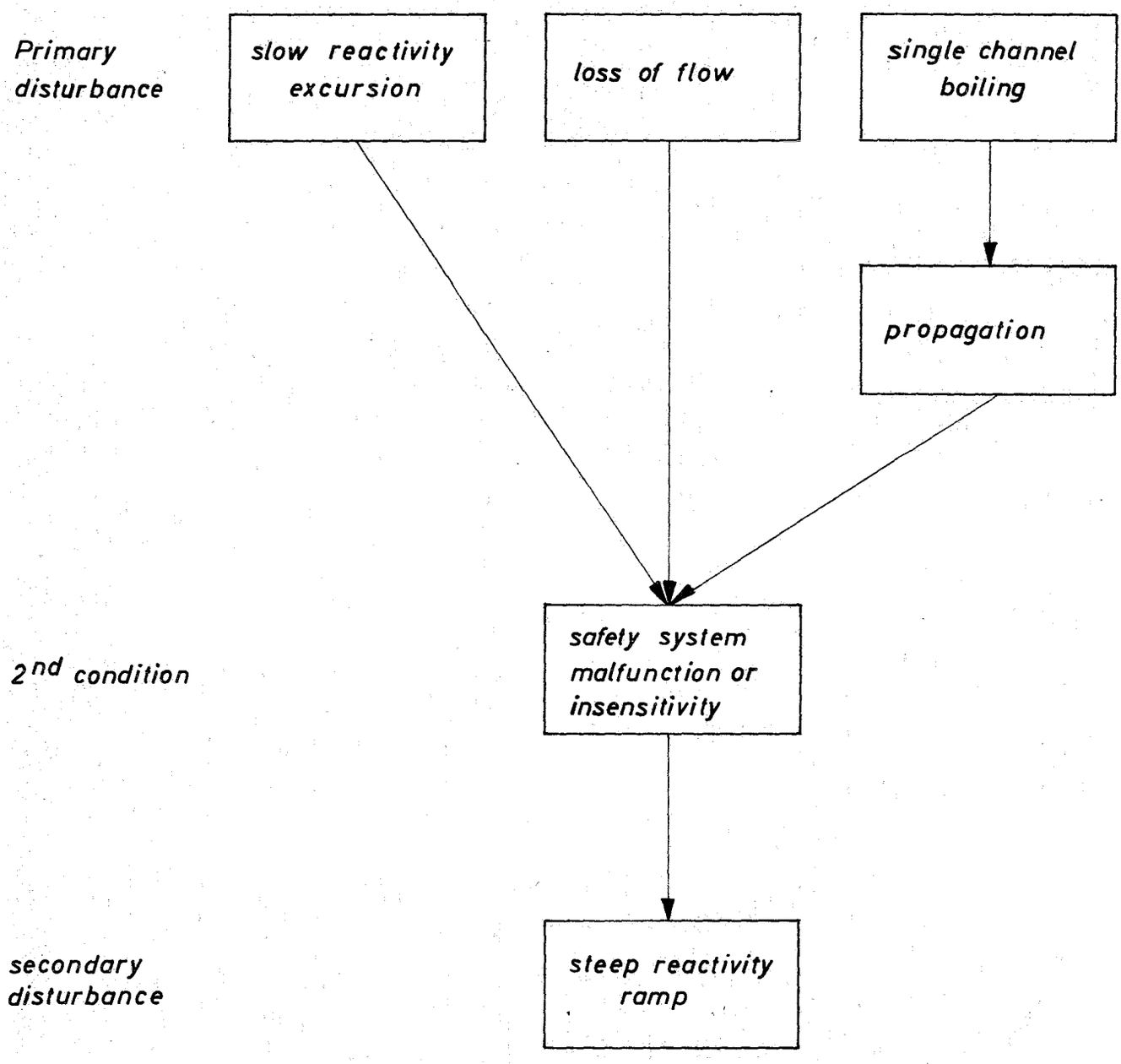


Fig.1 Chains of Events for Sodium Boiling Accidents

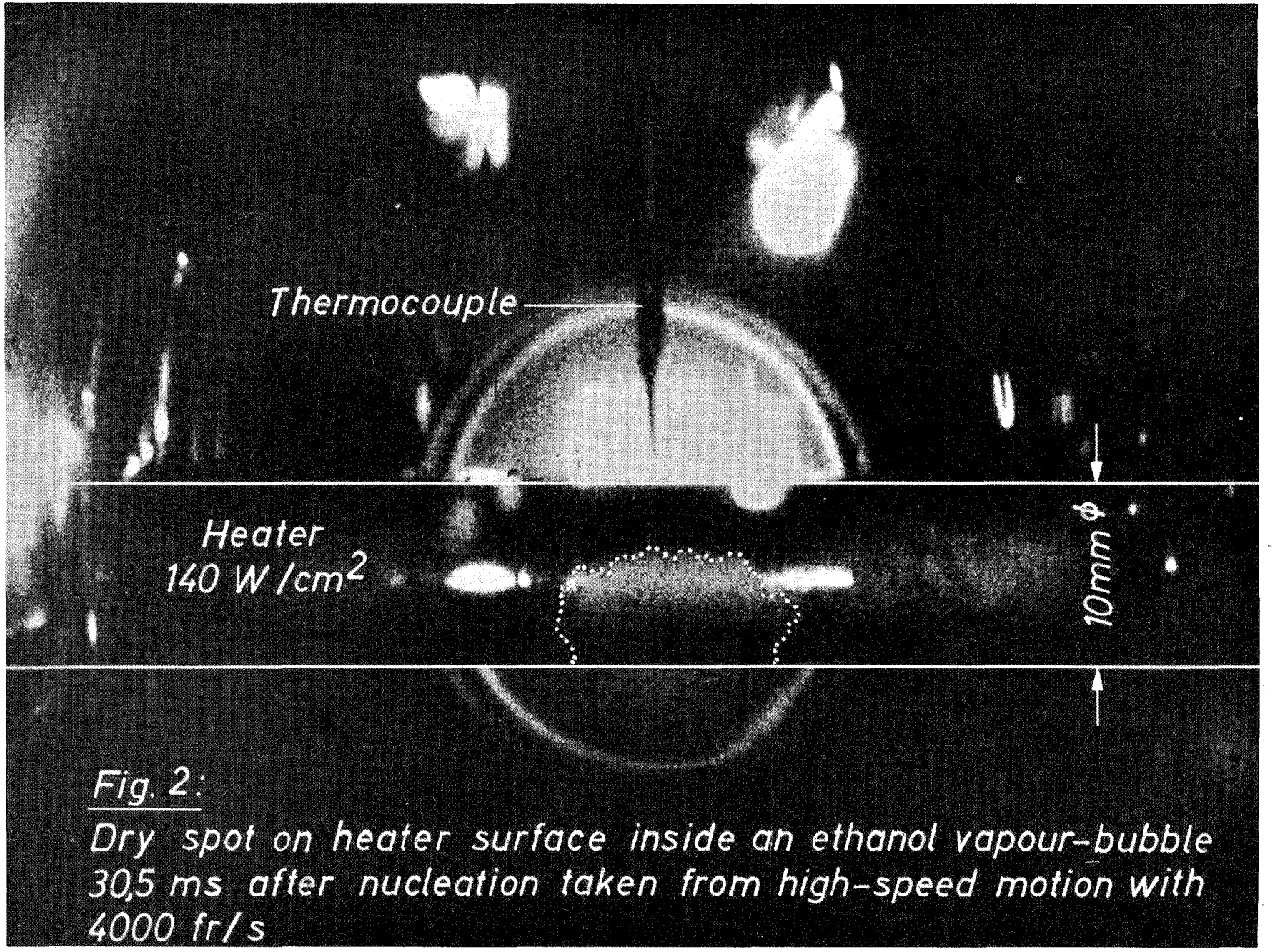


Fig. 2:
Dry spot on heater surface inside an ethanol vapour-bubble 30,5 ms after nucleation taken from high-speed motion with 4000 fr/s

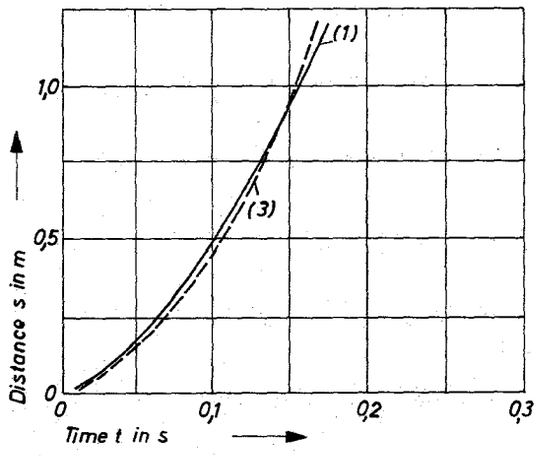


Fig. 3a: Stagnant potassium kinetic behaviour during boiling
(1) taken from Fig. 14 of Ref. 8
(3) calculated with BLOW

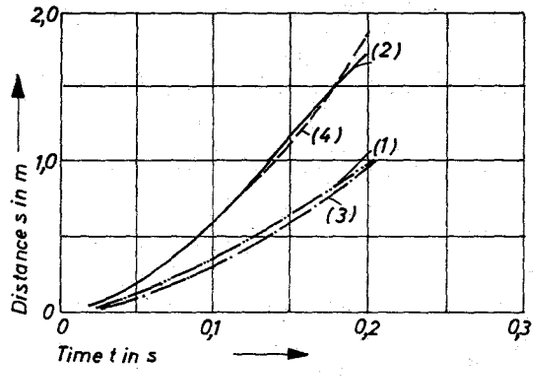


Fig. 3b: Natural convection kinetic behaviour during boiling
(1) and (2) taken from Fig. 15 of Ref 8
(3) and (4) calculated with BLOW

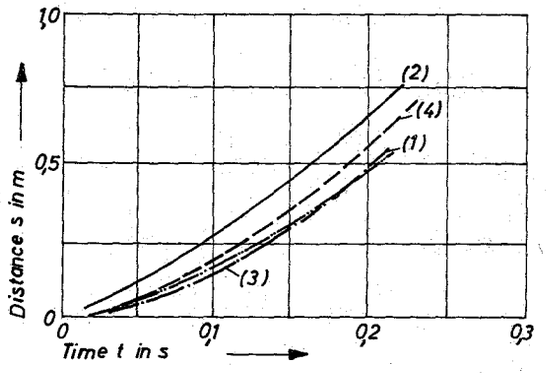


Fig. 3c: Forced convection kinetic behaviour during boiling
(1) and (2) taken from Fig. 16 of Ref. 8
(3) and (4) calculated with BLOW

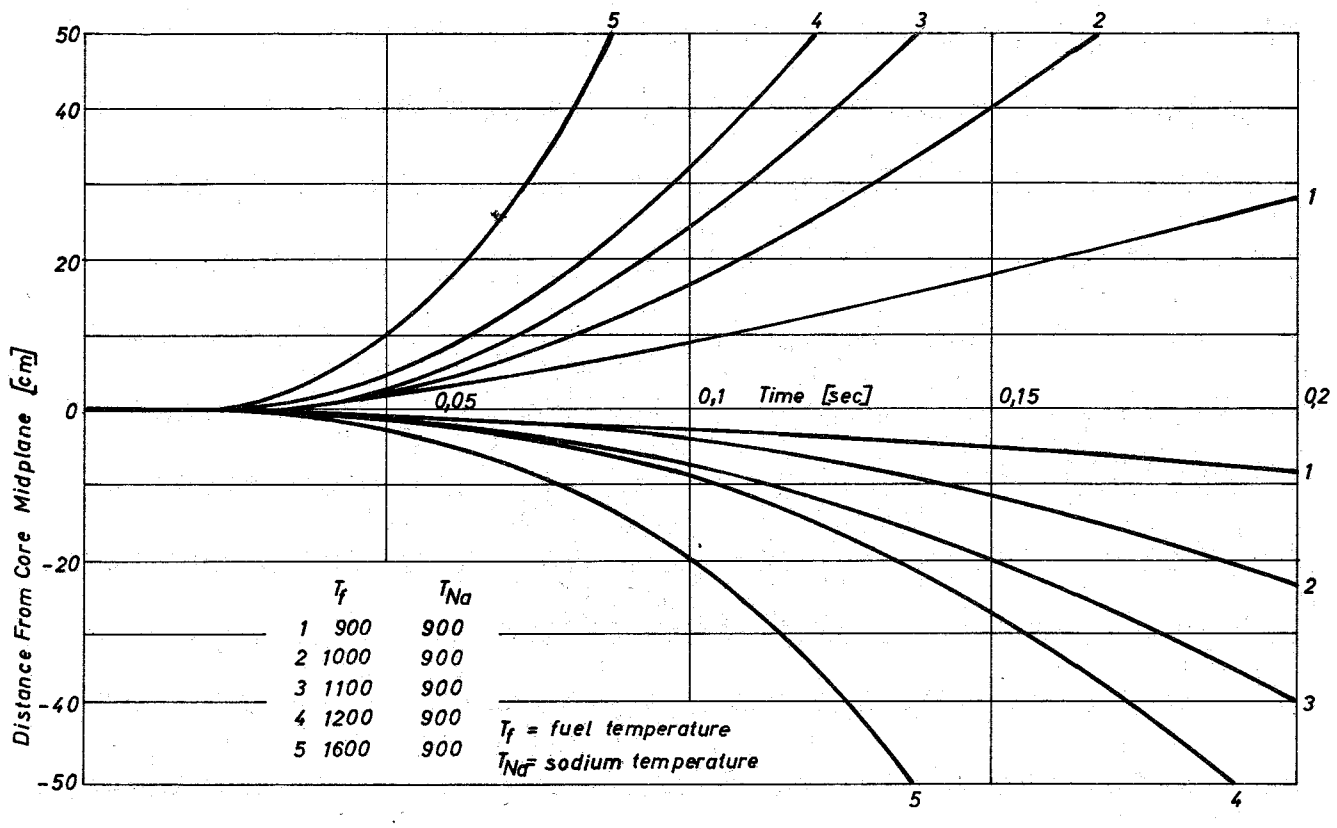


Fig. 4a: Sodium ejection with 20° C liquid superheat

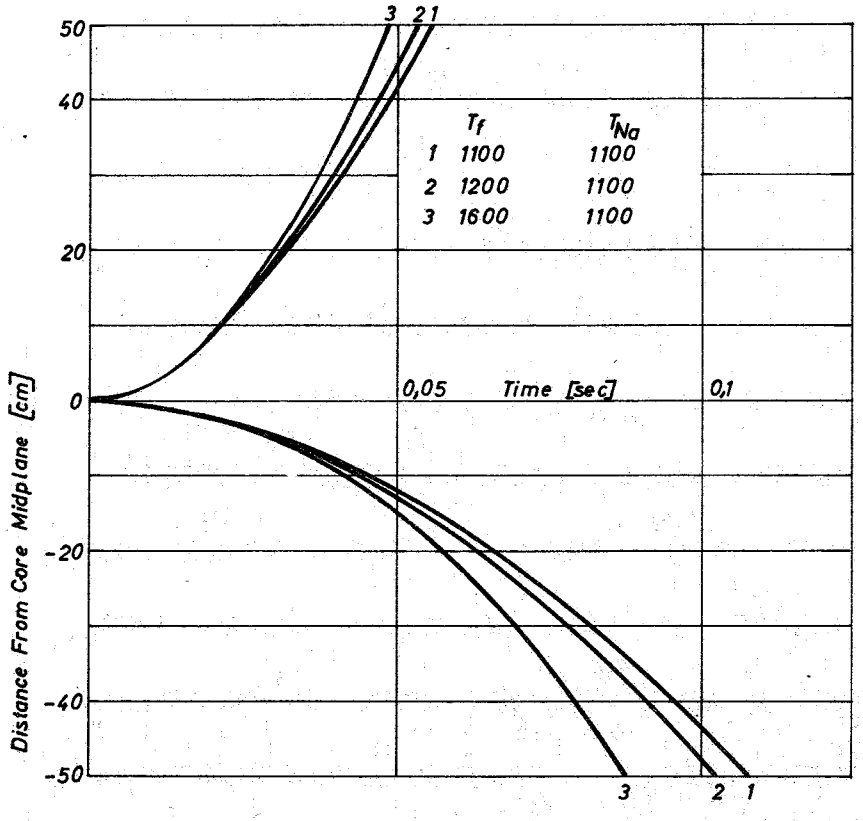


Fig. 4b: Sodium ejection with 220° C liquid superheat

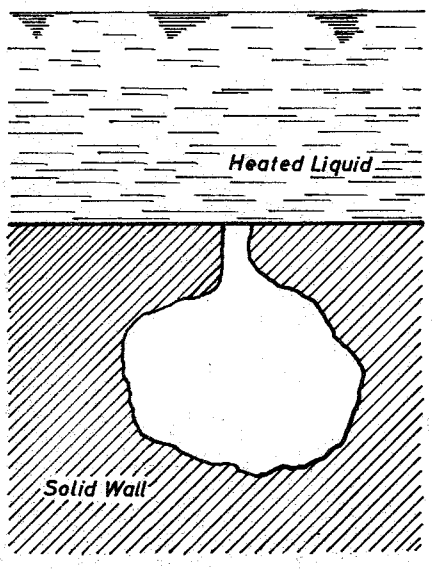
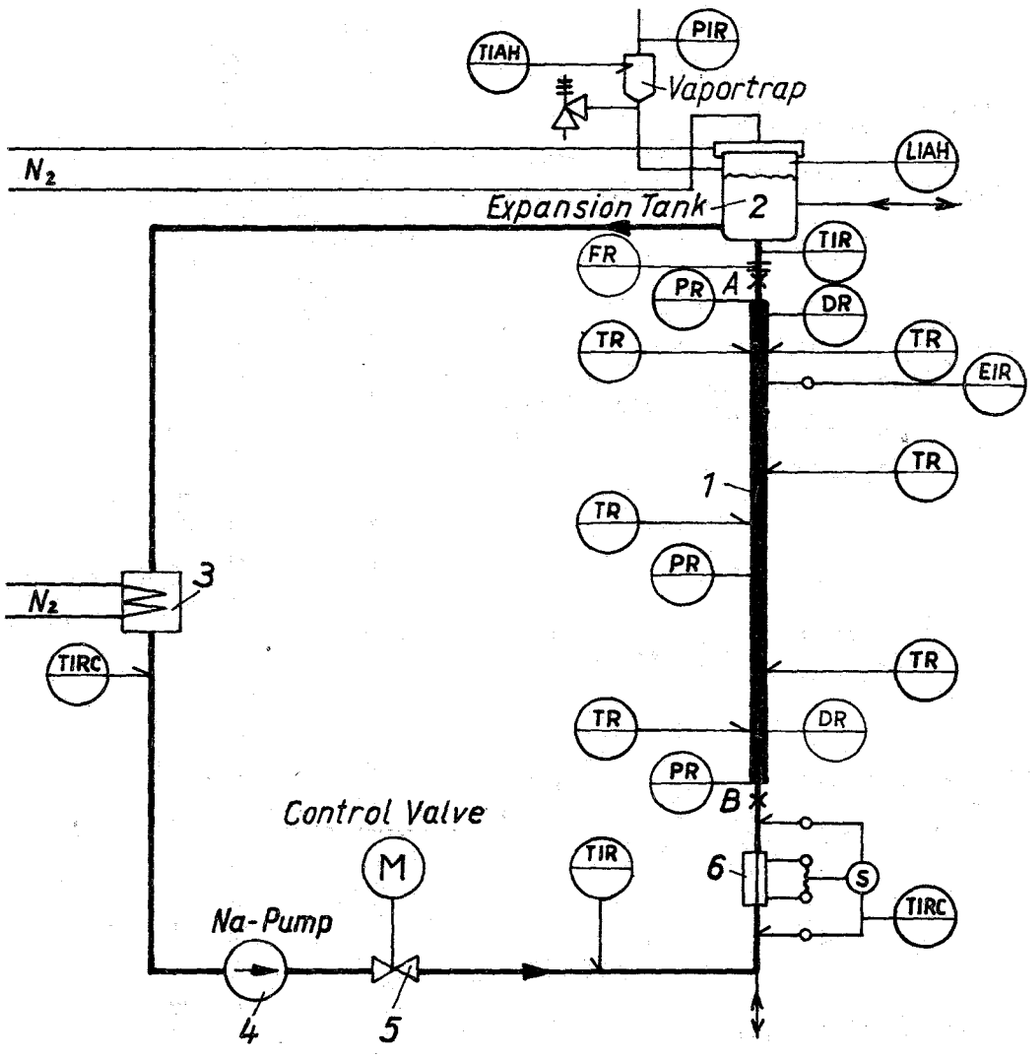
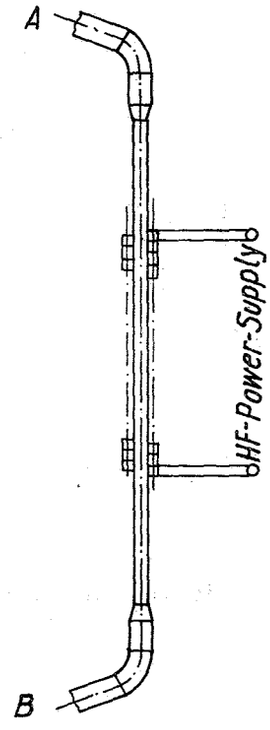


Fig. 5: Re-entry cavity





Power	E	Level	L
Temperature	T	Indication	I
Flow	F	Registration	R
Pressure	P	Alarm[High-Low]	A[HL]
Density	D	Control	C

◯ Indication Local

⊖ Indication or Registration on Operator Desk

Sodium-Loop

Testsection

Fig. 6 : Na2 Loop

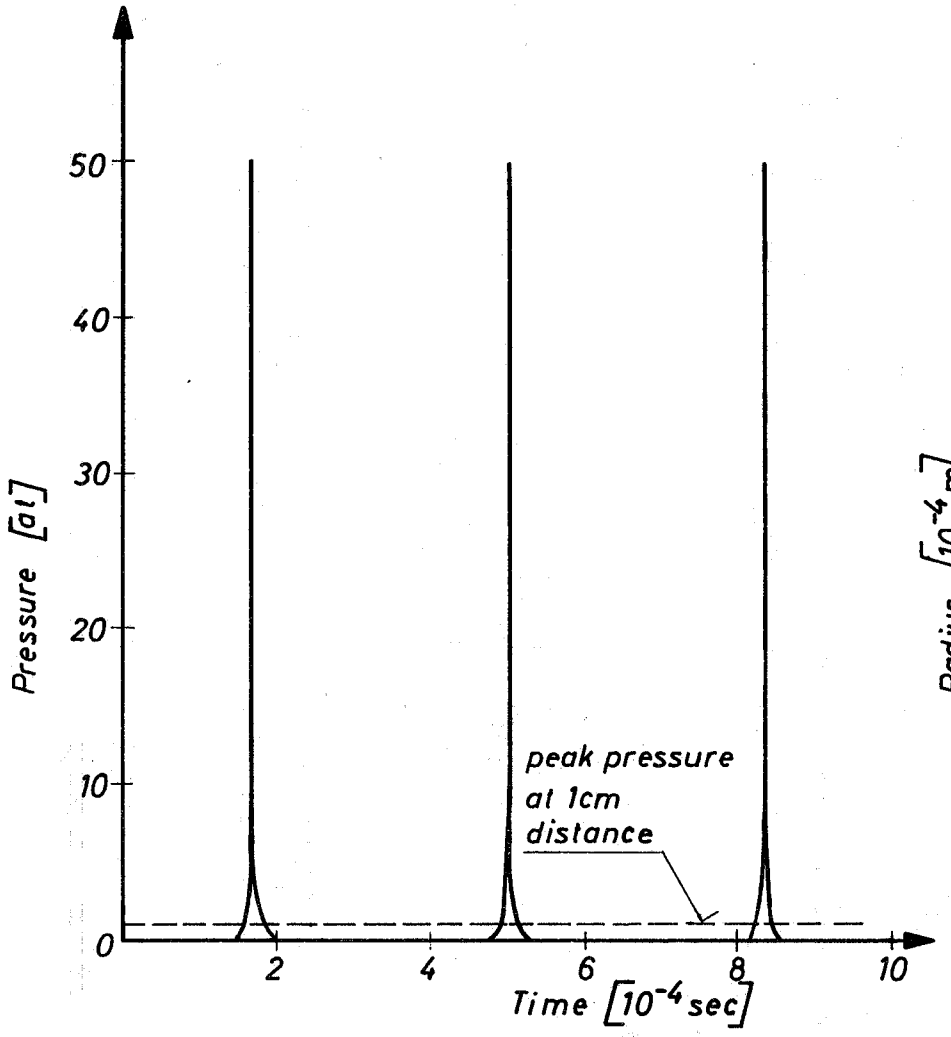


Fig. 7a: Pressure vs time inside a collapsing 1mm radius Na-vapour bubble in 500°C Na at p_∞ = 0,26 at

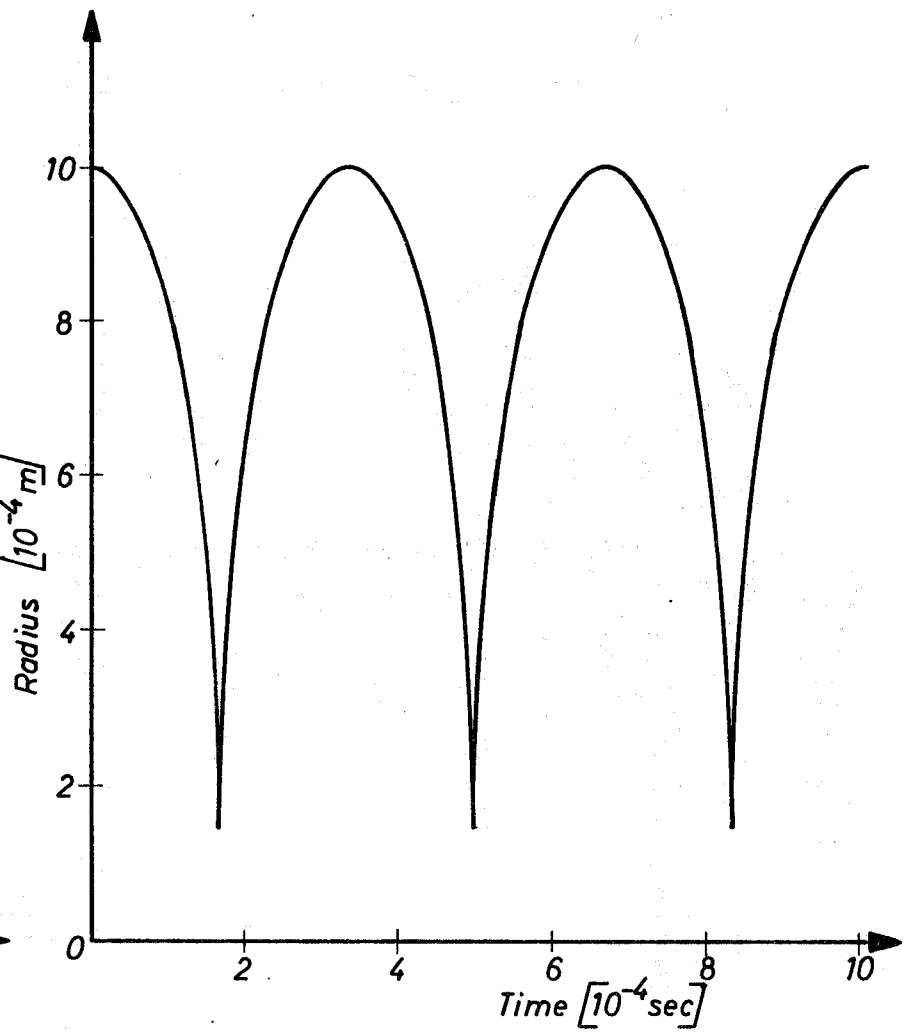


Fig. 7b: Radius vs time corresponding to Fig. 7a

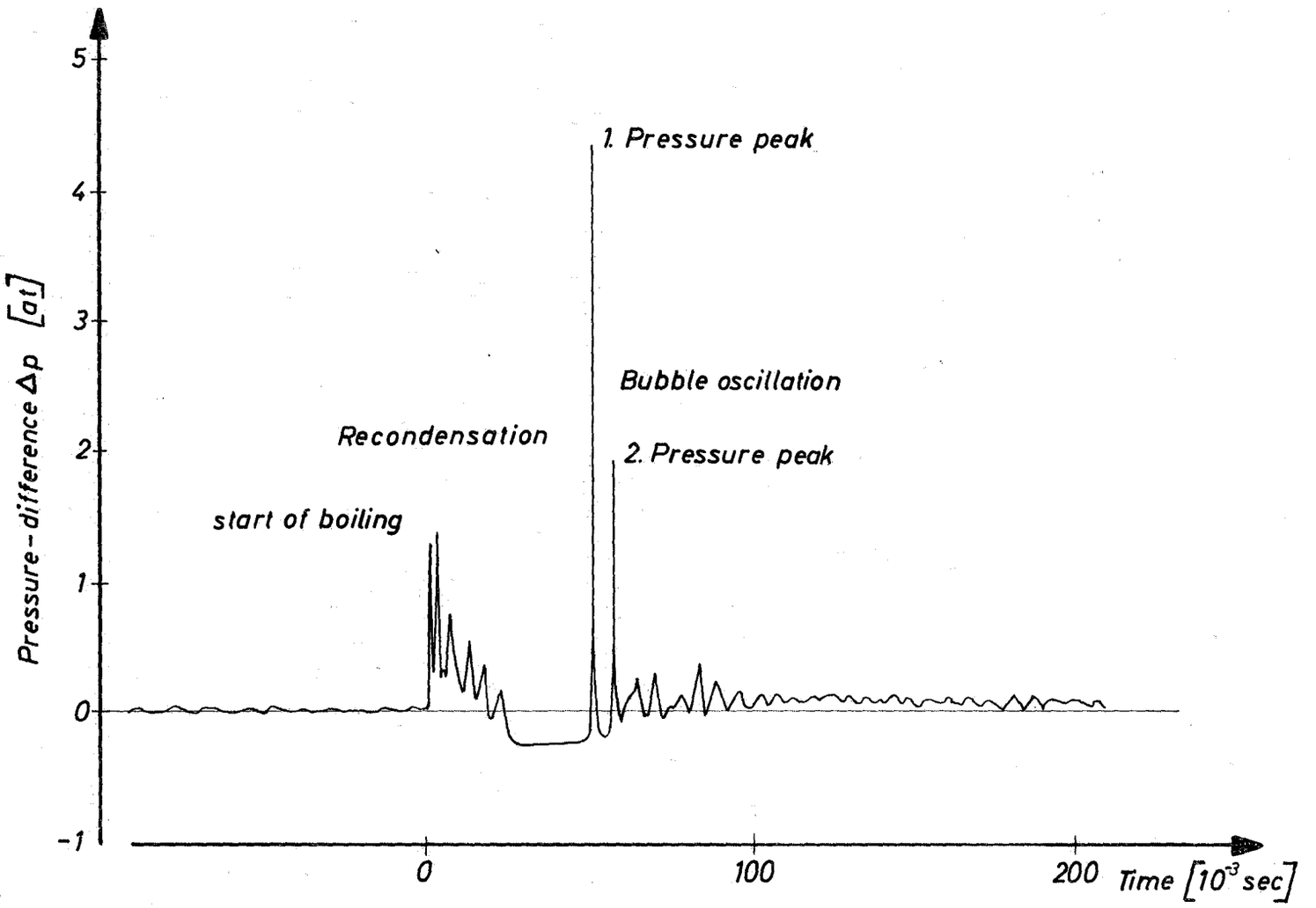


Fig. 8: Pressure - difference $\Delta p = p_{abs} - p_{system}$ vs time of a sodium boiling and recondensation experiment