MASTER

A Survey of the Current State of Knowledge
of Incipient Boiling Superheat in Sodium*

by

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**Work performed at Argonne National Laboratory under the sponsorship of the Advanced Reactor Safety Research Division of the USNRC.*

***Participant in the Spring 1979 Undergraduate Research Participation Program, January 8-April 27, 1979. This program is coordinated by the Argonne Center for Educational Affairs.*

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
I. SIGNIFICANT PARAMETERS.	3
A. Introduction.	3
B. Inert Gas Concentration	3
C. Oxygen Concentration.	5
D. Pressure.	8
E. Pressure-Temperature History Effect	8
F. Rate of Temperature Rise.	10
G. Heat Flux	13
H. Flow Rate	15
I. Operating Time on the System (Aging).	18
J. Surface Conditions.	21
K. Effect of Radiation	21
II. TESTS PERFORMED UNDER LMFBR CONDITIONS	23
III. CONCLUSIONS.	29
REFERENCES	31
APPENDIX	35

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Incipient Boiling Superheat ΔT of Sodium Versus Cold Trap Temperature CTT; $T_{\text{sat}} = \text{const.}$, Test Surface Materials: Stainless-Steel 4571, Ni, Fe, Cr.	6
2.	Incipient Boiling Superheat ΔT vs. Saturation Temperature T_{sat} of Sodium, Results of Different Test Series with "Hysteresis Effect".	6
3.	Superheat Histogram Evaluation (Bulk Superheat)	7
4.	Wall Superheat vs. Saturation Pressure.	9
5.	Effect of Rate of Rise of Heating-Wall Temperature on IB Superheat for Turbulent Flow of Sodium in an Annular Channel, and for a Heat Flux of (a) 50,000 Btu/h·ft ² , (b) 100,000 Btu/h·ft ² , (c) 200,000 Btu/h·ft ²	11
6.	Comparison of IB Superheat Measurements Obtained By Different Experimental Procedures for Turbulent Flow of Sodium in an Annular Channel	12
7.	Effect of Wall Heat Flux on IB Superheat, Showing the Relationship Between a Typical IB Curve and a Heat-Balance Line.	14
8.	Effect of Flow Velocity on IB Wall Superheat.	16
9.	Experimental Results Showing the Effect of Flow Rate on IB Superheat for Sodium in Turbulent Channel Flow Heat Flux = 200,000 Btu/h·ft ²	17
10.	Effect of Flow Rate on IB Wall Superheat.	17
11.	Results of Tests Performed Under "Temperature Transient Conditions" (a) Bulk Superheat vs. Velocity and (b) Wall Superheat vs. Velocity.	19
12.	Results of Tests Performed Under "Thermodynamic Transient Conditions" (a) Bulk Superheat vs. Velocity and (b) Wall Superheat vs. Velocity.	20

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Test Results from France et al. ³	23
II.	Test Results from Aberle et al. ²⁷	25
III.	Test Results from Ribando et al. ²⁸	26

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ABSTRACT

Superheat data obtained by various investigators indicate that many parameters affect this phenomenon. Controlling parameters appear to be inert gas concentration, oxide concentration, system pressure, pressure-temperature history, rate of temperature rise, heat flux, flow rate, operating time on the system, surface conditions, and radiation. Of these, the two believed most influential in controlling incipient boiling superheat are the inert gas concentration and oxide concentration. Experimental results for the heat flux and rate of temperature rise appear to be the most inconsistent.

I. SIGNIFICANT PARAMETERS

A. Introduction

Interest in liquid metal boiling has increased with the development of liquid metal cooled fast breeder reactors. An integral problem in analysis of liquid metal boiling is the degree of superheat achieved by the system prior to boiling inception since the violence of boiling initiation and subsequent void formation is strongly influenced by the magnitude of the superheat.

Experimental investigations into the problem of superheat in sodium have revealed that many parameters influence incipient boiling superheat (IBS). Those postulated to be significant are:

- inert gas concentration
- oxide concentration
- system pressure
- pressure-temperature history
- rate of temperature rise
- heat flux
- flow rate
- operating time on the system (aging)
- surface condition
- radiation

Much of the reported experimental data is contradictory, as the large number of operating parameters are difficult to control. Therefore, no cohesive theory which relates the relative importance of these parameter exists. However, many experimenters agree that the inert gas concentration and the oxide concentration are the two most influential parameters. Just as no comprehensive theory exists, no predictive model exists giving superheat values for given operating conditions. However, Kottowski and Savatter¹ estimated a range of probable superheats.

B. Inert Gas Concentration

Inert gas has two means of affecting IB superheat:

- a) as undissolved gas bubbles carried through the liquid,
- b) as diffusion of gas from surface cavities.

Experiments^{2,3,4} show that higher inert gas concentrations, or inert gas partial pressures, cause lower superheat.

This parameter is postulated to determine the incipient boiling (IB) event overshadowing the importance of such other parameters as heat flux, velocity effect and temperature ramp rate.

A liquid in a superheated state is in an unstable condition; any bubble of radius greater than about $10\mu\text{m}$ will nucleate boiling⁵ in a region which is more than a few degrees superheated. If gas entrainment occurs, nucleation

will occur via the entrained gas bubbles at low superheat. If no entrainment occurs, nucleation takes place in surface cavities.

Gas entrainment is a difficult parameter to detect or control, and many experimenters fail to report the inert gas concentration of their test systems. Most experimental systems have expansion tanks after the heated section where the hot sodium will pick up dissolved cover gas. Since the solubility of inert gas increases with temperature, the sodium will be super-saturated with dissolved argon once it reaches the cold portion of the loop. Argon (cover gas) bubbles form on the walls and when they reach the critical radius are swept off into the flow. Hence for loop type systems employing an inert cover gas the presence of entrained gas bubbles is likely.⁵

Kottowski and Grass obtained zero superheat in their test system of 6.8 mm i.d., stainless steel with a sodium flow of 3 ft/sec by injecting bubbles at a rate of 20 bubbles/sec. The original reference was not available and these were the results reported by Kottowski and Savatteri.¹ It would be interesting to check to see whether the 20 bubbles/sec was experimentally determined to be the critical rate of bubble injection to yield zero superheat.

Henry et al.² used two methods of achieving boiling inception in their experiments. Method (a) brought the loop up to temperature by using only the trace and guard heaters. The first boiling run was taken within 18 minutes of energizing the system. Method (b) used the test section heater plus the guard and trace heaters. The downstream end of the heater was maintained at $\sim 593^{\circ}\text{C}$ for 2-3 hours. Method (b) yielded much higher superheats. The proposed explanation was that method (a) did not allow the noncondensable gases in surface cavities time enough to go back into solution which results in high partial pressures and consequently lower superheats. Method (b) allowed gas to diffuse out of the cavities which produces a low partial pressure and higher superheat.

An additional discovery of their study was that when the surface was kept at an elevated temperature (590°C or greater) for several hours, the inert gas partial pressure in surface cavities could be neglected for the gas concentration present in this study.

Singer and Holtz⁶ made a mathematical analysis (assuming pool-boiling heat transfer processes) to determine the rate of inert gas loss from surface cavities during the heat-up period prior to an IB event. They found a high rate of gas diffusion from surface cavities that was dependent on the temperature at the start of heating, the depth of the sodium pool, and the heat flux. In this same study, they determined that nonspecification of the inert gas partial pressure in the gas cover blanket can cause an uncertainty in incipient superheat as large as 100°C .

Schultheiss⁷ found in his experiments that the effects of dissolved argon in pool-boiling experiments are random and not systematic. Other investigators concluded that inert gas was responsible for unexplained variations in IB superheat. However, these investigators used a more tubular experimental set-up with "as-received" surfaces whereas Schultheiss used polished surfaces with one artificial cavity. Perhaps the inert gas concentration is not an important variable in pool-boiling experiments.

France et al.³ performed flow rundown tests under LMFBR conditions. These tests are discussed further in Section 2; however, no specific parameters were isolated and studied. In the initial test displaying consistently zero superheat, the system was operated at steady-state conditions for 30.5 hours to allow the sodium to become saturated with the argon cover gas. The next test was run under the same operating conditions with a single exception: instead of 30.5 hours of steady-state operation, only 0.8 hrs were imposed. This test series showed high superheat. The author's conclusion was that the inert gas concentration was the only difference, since the 0.8 hr test series would be expected to have much less argon dissolved in the sodium. However, no actual measurements of inert gas concentration are reported to have been made. Finally, it is believed that the contamination of the sodium with argon significantly retards the wetting of stainless steel surfaces. Furthermore the degree of wetting is believed⁷ to determine nucleation sites, so this is an important parameter.

C. Oxygen Concentration

It has been observed^{8,9,10} that superheat decreases with an increase in oxygen concentration. Oxygen concentration is felt to overshadow other effects like type of heating surface, operating conditions and the pressure-temperature history effect.

Kottowski and Savatter¹ proposed the following extrapolation formula based on available experimental data to determine wall superheat as a function of oxide concentration:

$$\Delta T = -77 + \frac{163}{\log C} [^{\circ}\text{C}]$$

$$C = \text{O}_2(\text{ppm}) \text{ concentration} = \frac{C}{C_o}, C_o = 1 \text{ ppm}$$

This purely empirical formula can be applied to "non-treated" stainless steel surfaces in the range of 5-60 ppm O₂ impurity (employing coolant velocity of up to ~3 m/s).

The level of oxygen concentration may be controlled by the use of cold traps. The lower the cold trap temperature, the greater the system purity. Unusually high superheats have frequently been attributed to extreme system purity. Superheats of up to 600°F were reported by Grass, Kottowski and Spiller.¹¹

Schultheiss⁷ measured IB superheat vs. Na₂O on a stainless steel test surface. He also performed the same experiment with Ni, Cr and pure iron surfaces. His results, reproduced in Fig. 1, showed a maximum for both the stainless steel and chromium surfaces. Iron is unaffected by increases in oxide concentration and nickel shows a uniform decrease in superheat with increasing oxide level.

Fig. 1.

Incipient Boiling Superheat ΔT of Sodium Vs. Cold Trap Temperature CTT; $T_{sat} = \text{const.}$, Test Surface Materials: Satainless-Steel 457l, Ni, Fe, Cr.

At first, this effect was attributed to the free energy of formation of chromium oxide, and its dependence on temperature. However, it is now believed⁷ that the maxima were due to a kind of "hysteresis" effect of surface cleaning (cf. Fig. 2). After an operating time of ~ 3 hours the effect disappeared and the superheat decreased monotonically with increasing Na₂O concentration as expected.

Fig. 2. Incipient Boiling Superheat ΔT vs. Saturation Temperature T_{sat} of Sodium, Results of Different Test Series with "Hysteresis Effect". (Figure from Ref. 1).

Kottowski and Grass's⁸ experiments showed a strong influence of oxide concentration on superheating. As they did not try to isolate oxygen concentration as an independent variable, they did not obtain quantitative results on how oxygen concentration affects superheat. An approximate twofold increase in oxygen concentration produced a substantial decrease in IB superheat.

Logan et al.⁹ made 100 boiling initiation tests with cold trap temperatures (CTT) of 165, 150 and 120°C respectively. In all runs, the flow velocity was 3 ft/s (0.9 m/s) and inlet subcooling was 190°F (83°C). A histogram from Ref. 9 (Fig. 3) shows the effect of cold trap temperature (CTT) on superheat. The data from the 150°C CTT shows a lower superheat and greater range; however, since the oxide level differences are not that pronounced (4.5 ppm at 165°C, 2.8 ppm at 150°C), no real conclusions can be drawn. The distribution for the 120°C CTT shows a strong influence. There are weak peaks at 5°C and 15°C but otherwise the range of superheats is much greater, extending up to 50°C.

Fig. 3. Superheat Histogram Evaluation (Bulk Superheat)(Data from Ref. 9; Figure from Ref. 1)

Their conclusions are: increasing the oxide level decreases the superheat necessary to initiate boiling and also reduces the width of the superheat distribution.

The CCR Ispra lab performed similar experiments¹ with oxide levels of 17, 18.5, 30 and ~40 ppm. Tests were performed at a system pressure of 0.8 bar and velocity of 1.4 m/s (17 and 40 ppm) and 1.8 m/s respectively (18.5 and 30 ppm). Oxide level was maintained constant during a test. The distribution for the lower oxide concentration shows the same trend. At increased oxide concentrations boiling occurred with an IBS of 5°C for 30 and 40 ppm.

The results obtained by Logan et al.⁹ and Ispra¹ can not be rigidly compared as they used different methods of oxide determination. However,

these independent results from two different laboratories show good agreement which tends to support the purported importance of oxide level as a parameter.

D. Pressure

The theoretical basis for the effects of system pressure on IB superheats is based on the bubble equilibrium equation which determines the critical bubble radius required to initiate boiling by balancing internal and external pressures against the bubble surface tension.

The equation to determine the critical bubble radius is

$$r_{\text{crit}} = \frac{2\sigma}{P_v + P_g - P_l}.$$

The equation to determine system superheat, knowing r_{crit} , is

$$\Delta T = \frac{2\sigma}{r_{\text{crit}}} \frac{v_{fg}}{\Delta h} T_{\text{sat}}$$

where

ΔT is system superheat $T - T_{\text{sat}}$,

P_v is vapor pressure,

P_g is partial pressure of gas,

P_l is local pressure of liquid,

σ is surface tension,

Δh is latent heat of vaporization,

v_{fg} is the difference in liquid-vapor specific volume.

Specifying the system temperature T and pressure P_l determines r_{crit} from the first equation since relationships for $\sigma(T)$ and $P_g(T)$ are available. The second equation yields ΔT since P_l implies T_{sat} which then determines Δh and v_{fg} .

This theoretical argument is supported by many experiments. Results achieved by Logan et al.⁹ serve to illustrate the generally obtained effect for wall superheat vs. saturation temperature and/or pressure (Fig. 4). Low boiling pressure yields greater data scatter. The reasons for this are (1) the large superheats present at low pressure, and (2) a greater tendency for different cavities to nucleate from run to run.

E. Influence of Pressure-Temperature History on IB Superheat

The original model introduced by Holtz¹² arose from trying to predict IBS as it depends upon the operating history of an experimental apparatus

Fig. 4.

Wall Superheat vs. Saturation Pressure.
(Ref. 9)

without measuring the size of the surface cavities directly. This model used the bubble equilibrium equation in conjunction with its cavity interaction in an attempt to predict bubble radius size for nucleation. The model made several simplifying assumptions, the major one being that the partial pressure of inert gas was zero. For systems where the partial pressure is near zero, the model¹³ predictions are close to experimental data. Chen and Dwyer¹⁴ extended the theory to include the effects of inert gas in the wall cavity nucleation sites.

The model is based on the assumption that for a given fluid-surface combination there are three independent variables having influence: a) deactivation pressure (variation in the system pressure) b) deactivation temperature (subcooling) and c) boiling pressure. The superheat required for incipient boiling is the dependent variable. The pressure-temperature history is believed¹ to be a critical variable in determining incipient wall superheat due to cavity deactivation during pressurization and subcooling conditions.

Some investigators^{13,2} have demonstrated the importance of establishing an "operating history." It has been found that a boiling surface can exhibit a "hysteresis" effect, but it has also been found that the results of previous histories can also be lost when previously active sites become de-activated and new active cavities are formed by cracks in the heating surface caused by high wall superheat. Holtz, Fauske and Eggen,¹³ conducting their test in an apparatus without inert gas, discovered that a previously established history can be lost. To regain that history the previous pin pressure and temperature conditions had to be applied for at least 20 minutes before each run. This yielded good incipient boiling superheat correlation with the Holtz theory when the ratio of receding to advancing rate of curvature (R/R') was 0.34.

France et al.³ used the results obtained in series C.1 and E.1 of their experiments to test the pressure-temperature history effect. These tests were performed with low, but equilibrium, inert gas concentration in the sodium.

Although the experimental data was limited, they found good agreement using the proper conditions and a R/R' ratio of 1.0.

Henry et al.² found the reentrant cavity model to be effective in predicting the superheats found in their system as long as they accounted for the previous history of noncondensable gases. They experienced the "hysteresis" effect in which, after applying a higher system pressure and then returning to the original system pressure, a greater superheat was required to initiate boiling than in the runs prior to the higher pressure. However, this effect was short-lived and in succeeding runs the IB superheat decayed back to its original values.

Schultheiss⁷ performed experiments with single artificial cavities which showed no correlation to the pressure-temperature history. Kottowski¹ also tried without success to obtain experimental corroboration. Schultheiss objects to the limited view presented by the model of the nucleation process.

F. Rate of Temperature Rise

This parameter is determined by how boiling inception is achieved. There are several methods to initiate boiling (at a given static pressure): a) holding inlet temperature and flow rate constant and gradually increasing the heat flux; b) holding inlet temperature and flow rate constant and increasing the heat flux in steps; c) holding inlet temperature and flow rate constant and imposing a single one-step increase in power to the heater; d) holding heat flux and flow rate constant and gradually increasing the inlet temperature; e) holding heat flux and flow rate constant and increasing the inlet temperature in steps; f) holding heat flux and inlet temperature constant and gradually decreasing flow rate; g) holding heat flux and inlet temperature constant and decreasing the flow rate in steps.¹⁵ The variety of ways to achieve boiling inception illustrates the wide range of possible temperature ramps.

The method most commonly employed to initiate boiling has been to use method (c), i.e. apply the power in a single step. This method is relatively simple to execute and is of particular interest since it simulates a sudden burst of reactivity in a fuel element. However, this method employs a sharp temperature ramp which is postulated to mask the true effect of the heat flux. Although the average temperature ramp is high the instantaneous temperature rise rate at which boiling occurs is lower since steady-state conditions are approached before boiling onset.

Dwyer et al.¹⁵ claim that it is the failure to account for the temperature ramp which causes so much data scatter. In their experiments they separated the heat flux effect and rate of temperature rise, which are not independent when method (c) is used. They employed methods (a), (c) and (d) in their study with the majority of tests conducted using (d). A fixed parameter for these tests was the temperature ramp.

They obtained a clearcut effect of temperature ramp on IBS. As the temperature ramp approached zero, the IB superheat approached a fixed limit; here it was 40°F independent of heat flux (Fig. 5).

Fig. 5. Effect of Rate of Rise of Heating-Wall Temperature on IB Superheat for Turbulent Flow of Sodium in an Annular Channel, and for a Heat Flux of (a) 50,000 Btu/h·ft² (b) 100,000 Btu/h·ft² (c) 200,000 Btu/h·ft². (Data from Ref. 15; Figures from Ref. 14).

They compared data obtained by using each of the three methods (cf. Fig. 6) and found that a given rate of temperature rise produced the same superheat, independent of which method was used. Using method (c), IB superheat was not achieved until almost steady-state conditions were reached, which agrees with the results achieved by Logan.⁹

Fig. 6.

Comparison of IB Superheat Measurements Obtained by Different Experimental Procedures for Turbulent Flow of Sodium in an Annular Channel. (Ref. 15).

Method (c) was used for two different heat fluxes: runs 57-59 at heat flux of $100,000 \text{ Btu/h}\cdot\text{ft}^2$ and runs 60-62 at heat flux of $200,000 \text{ Btu/h}\cdot\text{ft}^2$. As shown in Fig. 6, significantly higher superheats were reported for the higher heat fluxes, i.e. superheat was very dependent on the steady-state value of the heat flux. Using method (c), as the heat flux increased from $50,000$ to $100,000$ to $200,000 \text{ Btu/h}\cdot\text{ft}^2$, the superheat increased from 76 to 126 to 233°F . The reason for this, they deduced, is the high-temperature ramps in the early stages of the temperature transients precluded the possibility of lower IB superheat. They concluded that if the temperature rate were held constant, IB superheat is the same independent of how the test is conducted. If, however, the temperature ramp is not constant, the magnitude of IBS depends on the experimental procedure.

Since an IB event is stochastic in nature, the longer the system is kept at a given temperature, the greater the probability for an IB event to occur at that temperature. Therefore, higher temperature ramps raise the magnitude of IBS, all other parameters being equal.

In the discussion following the presentation of the above paper, Fauske suggested that the temperature rate effect was only apparent and it was due to inert gas effects. For constant velocity, the inert gas mass of a bubble would tend to decrease with increasing temperature ramp, thereby explaining the noted trend in the data so long as entrained bubbles are present in the sodium.

Dwyer et al. refuted this argument by saying that the inert gas mass in the bubble would tend to increase (rather than decrease) with increasing temperature ramp since greater temperature ramps allow less time for the inert gas to diffuse out of the bubble into the sodium where it would be more soluble, i.e., the greater the temperature ramp, the lower the IBS because of the greater inert gas concentration in the bubble. Since the opposite effect was noted, they concluded inert gas effects were not responsible. Also, in the course of conducting their experiments Dwyer et al. noted that if the temperature ramp were suddenly lowered, boiling inception would occur provided the wall temperature was sufficient. This was also construed to mean that the kinetics of inception were due solely to temperature ramp.

Winterton,⁵ in a theoretical analysis on liquid metal superheat in forced convection, also questions the results obtained by Dwyer et al.¹⁵ as they do not fit his theory. The superheats obtained by Dwyer et al. do not tend toward zero as the temperature ramp approaches zero; the scatter of points (considering the statistical nature of an IB event) is insufficient and the increase of superheat with heat flux is not predicted. He assumes these effects are a consequence of Dwyer's choice of low flow velocity, which is appreciably less than that of other investigators. This low velocity allows for extremely large gas bubbles to form whose passage through the test section disturb the flow. Winterton claims this passage of gas bubbles is detectable in Dwyer's data although the authors have misinterpreted its significance.

Kikuchi et al.¹⁶ in their loss-of-flow experiments investigated the effect of wall temperature ramp rate on IB wall superheat. Their range of temperature ramp rate was much wider than those used by Dwyer et al. The results of their data show no strong effect of temperature ramp rate on IB wall superheat.

From the contradictory published results, no conclusion is justified regarding the effect of temperature ramp rate on IBS.

G. Heat Flux

No theoretical basis for an influence of heat flux on IBS exists, leading some experimenters to conclude that any observed effect is only apparent and is caused by variation in another system parameter. Since, heat flux influences temperature ramp, this effect could be examined as a potential correlation in that light. The observed effect is very dependent upon experimental procedure; various experimenters have reported that IBS increases, decreases or is unaffected by an increase in heat flux.

Possible explanations for the apparent effect attribute it to inert gas concentration or rogue nucleation occurring at sites beyond the axial location of highest temperatures in the test section. Kottowski and Savatter,¹ who take no stand regarding the effects of this parameter on IBS, caution that in future studies of this effect, the inert gas partial pressure must be kept constant, or it may mask other phenomena. Dwyer et al.,¹⁵ as explained earlier, contends that to measure the true heat flux effect, the rate of temperature rise must be held constant.

Dwyer et al.¹⁷ report that the following experimenters have observed an increase in IBS for sodium with an increase in heat flux: Peppler and Schultheiss¹⁸ found IBS increased from ~65 to ~151°F as the heat flux was increased from 203,000 to 488,000 Btu/h·ft²; Schleisiek¹⁹ found IBS increased from ~113 to ~212°F as the heat flux was increased from 600,000 to 1,190,000 Btu/h·ft².

Dwyer et al.¹⁷ claim that the heat flux is an important independent variable when boiling inception occurs at the point of highest temperature in the test section channel. Data is unreliable at low heat fluxes as rogue nucleation occurred in the preheater or in the inlet region of the test section.

As mentioned previously, Dwyer et al.¹⁷ have studied various methods of achieving boiling inception. They found that two different curves are appropriate for predicting IBS, depending on which method is used (see Fig. 7). Line bcd: values of pressure, velocity, inlet temperature and test section geometry are fixed; superheats due to sudden power bursts (method (c) of the previous section) fall along this line. Curve fcg: constant pressure, velocity and temperature ramp with heat flux the independent variable (method (d) in the previous section); superheats which are the result of gradually increasing inlet temperature, holding heat flux and flow rate constant, fall along line fcg. Point c is the break off point; below c, the constant temperature ramp has a greater superheat than a sharp temperature ramp; above c, the opposite effect is true.

Fig. 7.

Effect of Wall Heat Flux on IB Superheat, Showing the Relationship Between a Typical IB Curve and a Heat-Balance Line. (Ref. 17).

The IB curve is a function of the rate of rise of the heating wall temperature; the heat balance line is given by:

$$T_w - T_{sat} = q \left[\frac{1}{h} + \frac{2r_1L}{vpc_p(r_2^2 - r_1^2)} \right] + (T_{in} - T_{sat})$$

c_p = specific heat

v = average linear velocity

ρ = density
 L = heated length
 q = heat flux
 r_1 = inner radius of annulus
 r_2 = outer radius of annulus
 T_{in} = temperature of inlet stream
 T_w = temperature of heating surface
 T_{sat} = saturation temperature
 h = heat transfer coefficient

Dwyer et al.¹⁷ concluded for a laminar flow, with either the temperature ramp or the heat flux approaching zero, that there would be no significant effect of heat flux on IBS for liquid metal.

Holtz and Singer⁶ claim that the heat flux effect is secondary to the effect of inert gas partial pressure. They showed that superheat decreased with an increase in heat flux for a series of experiments in which only the heat flux was varied. However, they also showed that superheat can increase with an increase in heat flux if the tests are conducted without establishing the proper initial conditions prior to each run.

In another series of experiments²⁰ they found that cavity inert gas partial pressure varies from run to run. Since this is presumed to be significant in determining the heat flux effect, this uncertainty causes either an increase or decrease in the superheat with an increase in heat flux depending on whether the heat flux is successively increased or decreased. For experiments with no inert gas present, it has been found that the superheat is independent of heat flux, which is additional support for that theory.

Singer¹⁰ suggested that the mobility of inert gas between active nucleation sites and the liquid can result in the observed velocity effect. Since the solubility of inert gas increases with temperature, gas lost from nucleation sites during the heat-up period prior to and during boiling may go back into solution during the cooling time between tests.

The influence of heat flux shows much contradictory data; no clearcut effect can be determined.

H. Flow Rate

This variable, which affects the system turbulence, is also a highly disputed parameter. It has a clearcut observed effect: an increase in flow rate causes an exponential decrease in IBS, but there is no strong agreement as to its theoretical basis. Therefore, many experimenters feel the observed effect is due to variations in other system parameters and thus feel flow rate is not an independent variable.

One explanation that has found at least partial acceptance is the one proposed by Pezzilli et al.²¹ In short this theory proposes the existence of a minimum critical Reynolds number. At this Reynolds number and below, the IBS is the same as it would be for pool or laminar-flow boiling. As the

Reynolds number increases above this number, the IBS decreases. The data of Kikuchi et al.²² shows good agreement with this semi-theoretical model as illustrated in Fig. 8.

Fig. 8.

Effect of Flow Velocity on IB Wall Superheat. (Ref. 17).

Fauske, Holtz and Singer²³ postulate that rogue nucleation sites could be responsible for the flow rate effect. Failure to specify the site of boiling inception is a common flaw in much reported superheat data. Dwyer et al.¹⁷ raised objections to the postulation on two grounds. First, their study carefully measured the site of boiling inception which was found to approximately coincide with the point of maximum heater temperature. Second, Dwyer et al. included in their reports data from the studies of four others who also observed the velocity effect. It is highly doubtful that all five investigators experienced the effects of rogue nucleation.

The data of Logan et al.⁹ shows unmistakably that bulk superheat decreases noticeably, both in magnitude and extent of variation, as velocity increases from 3 ft/s to 9 ft/s:

Range of superheat values at 3ft/s: 10 to 132°F;
Range of superheat values at 9ft/s: -29 to -13°F.

The bulk superheat approaches zero beyond a velocity of ~4 ft/s. This trend has been also noted by other investigators.^{9,17}

Such an effect could be due to the increased system turbulence which would cause a more thorough fluid mixing and would limit the range of maximum superheat. This decrease in superheat prevails although the heat flux required to initiate boiling increases with velocity.

The wall superheat also decreases significantly with an increase in velocity; i.e., the fluid temperature near the wall approaches the local bulk fluid temperature. Extrapolating the results of these experiments to full-flow LMFBR velocities (flow velocity ~30 ft/s) Logan et al.⁹ conclude that subcooled nucleate boiling (i.e., negative superheat) will exist at boiling inception.

As a further part in their research, Logan et al. conducted superheat studies under flow coastdown conditions. These results taken under moderate transient flow conditions (boiling achieved ~26 seconds after start of flow reduction) are very similar to those previously obtained under steady flow conditions for velocities greater than 3 ft/s.

Dwyer et al.,¹⁷ as previously mentioned, carefully measured location of boiling inception and controlled the rate of temperature rise. The limited data they obtained illustrated a large effect of flow rate on superheat (cf. Fig. 9). Unfortunately, the study was terminated without sufficient data to establish the effect.

Fig. 9.

Experimental Results Showing the Effect of Flow Rate on IB Superheat for Sodium in Turbulent Channel Flow Heat Flux = 200,000 Btu/h·ft². (Ref. 17).

Kikuchi et al.²² in their single-pin channel experiments, conducted under steady-state conditions, also illustrate the velocity effect. The IB wall superheat reported by Schleisiek¹⁹ are much higher than those of other investigators. This is perhaps due to the influence of the high-frequency induction heater used in the experiment on the thermocouple voltages. See Fig. 10 for graphs of data obtained by Kikuchi and others.

Fig. 10.

Effect of Flow Rate on IB Wall Superheat. (Ref.22).

Henry et al.² believe that the velocity effect is not an independent variable and is actually due to rogue nucleations. Two of their objections to the majority of published superheat data are that the location of boiling inception is not recorded and that the investigators fail to specify entrained gas content (Dwyer et al.'s test measured the location of boiling inception but not entrained gas content). The test section used by Henry et al. was instrumented to detect both the axial location of boiling inception and the entrained gas content. They found (contrary to Dwyer et al.'s data) that the

axial location of inception does not necessarily coincide with the point of maximum superheat. The results of Henry et al. show that when the experiments are interpreted on the basis of maximum superheat, and all nucleations are included, the incipient superheat appears to decrease with increasing velocity. Several of the boiling runs were actually caused by nucleations from gas bubbles passing through the system; when the acceptable data were restricted to nucleations occurring within the superheated zone, and the point of nucleation is known, any dependence on system velocity appears to be within the normal scatter of data rather than a systematic effect.

In the work of Henry et al., all gas bubble nucleations at 4.8 ft/s and below were caused by a single bubble or group of bubbles passing through a saturated or superheated region. For higher system velocities, the gas detection nozzle indicates a significant average gas volume fraction in the coolant; for such cases, the coolant began boiling at zero bulk superheat. Thus although Henry et al. found no direct velocity effect, it is likely that at sufficiently high system velocities there would have been no bulk superheat.

Kottowski and Savatter¹ concluded that there is a velocity effect, but they also feel that it is only apparent. They suggest that it is a consequence of mass flow rate in a particular flow channel, a feature which is in accord with an all liquid heat balance.

Experiments were performed at Ispra¹ to determine boiling inception (however, gas entrainment was not controlled because no instrumentation was available). The following boundary conditions were applied:

A. Temperature transient conditions

- (i) constant system pressure (0.5 bar)
- (ii) constant temperature ramp, $\Delta T/\Delta t$
- (iii) constant inlet temperature

B. Thermodynamic transient conditions

- (i) constant temperature gradient
- (ii) steady-state thermo-hydraulic conditions
- (iii) decrease of the system pressure at constant rate up to boiling.

Tests were conducted under both sets of conditions (see Figs. 11 and 12). Under the conditions of test (A) the bulk superheat exhibited the usual velocity effect. Test (A) showed no effect of velocity on wall superheat. The difference between tests conducted under (A) and (B) are only qualitative. The velocity effect is less noticeable under method (B) because boiling starts primarily in the exit region of the test section.

I. Operating Time on the System (Aging)

It is important to discover the long term, if any, effects of operating time on incipient boiling superheat. There are postulated effects of both short and long term.

The short term effect of operating time is to cause an increase in IBS with time.

(a)

(b)

Fig. 11. Results of Tests Performed Under "Temperature Transient Conditions"
 (a) Bulk Superheat vs. Velocity
 and (b) Wall Superheat vs. Velocity.
 (Ref. 1).

(a)

(b)

Fig. 12. Results of Tests Performed Under "Thermodynamic Transient Conditions"
 (a) Bulk Superheat vs. Velocity and
 (b) Wall Superheat vs. Velocity.
 (Ref. 1).

This trend is suggested to be due to the loss of inert gas from surface cavities, usually accomplished within the first few boiling runs. A second short term effect involves the reduction of oxides in the cavity sites.

Over longer periods of time, it is felt that IBS may decrease due to new nucleation sites created by cracks and fissures developing in the test system.

Several experimenters observed the short term aging effect. Among these are Marto and Rohsenow²⁴ who noticed that earlier runs had lower superheats. Peppler and Schlechtendahl⁴ and Peppler and Schultheiss,¹⁸ Dwyer et al.¹⁷ and France et al.³ noticed no aging effect on their operating system. France et al. obtained consistently zero superheats in running their test without interruptions.

Logan et al.⁹ observed a negative aging effect. This they attributed to gross changes in the surface condition due to progressive corrosion. The first run at 5 psia spanned almost the entire superheat range while the final run at 5 psia yielded a very narrow superheat range with intermediate magnitude.

J. Surface Conditions

It is generally observed that rougher surfaces cause lower superheat, since rougher surfaces offer more nucleation sites.

The experimental surface conditions studied by Marto and Rohsenow²⁴ and Edwards and Hoffmann²⁵ include: polished finish, "as received" porous coating, or artificial cavities. More polished finishes have higher superheats and exhibit more data scatter, whereas superheat data is most precise and lowest for artificial cavities.

However, Singer and Holtz²⁰ feel that the effect of surface conditions is not an independent variable. They imposed the same pressure-temperature history conditions on two different test surfaces: one mirror finish and the other sand blasted for ~1/2 hour before each run. The results did not show any sensitivity to the surface finish. The authors concluded that the critical radius size for nucleation is determined by pre-boiling history and not by the gross surface roughness. They did concede that perhaps the changes in IBS due to differences in surface roughness were relatively small compared to the magnitude of the IBS even without imposing pre-boiling conditions before conducting the test.

K. Effect of Radiation

Limited studies have been done on the effects of radiation on IBS; conclusions thus far are that IBS is not affected by thermal neutron flux. However, much of the work done on this topic is theoretical, and many simplifying assumptions were used.

Claxton²⁶ theoretically proved that radiation induced boiling in the bulk of the liquid can not occur for pressures below 10 atm. Singer and Holtz²⁰ found no effect of radiation on IBS in pool boiling of sodium on a stainless steel surface with relatively large cavity sizes under conditions where the thermal-neutron flux was estimated to be 2×10^{11} n/cm²·s.

More experimental work is needed in this area before its possible effect can be entirely ruled out.

II. TESTS PERFORMED UNDER LMFBR CONDITIONS

France et al.³ conducted experiments in a loop designed to simulate a single LMFBR fuel element. The purpose of their experiment was to test the hypothesis that a system operating under LMFBR conditions for a length of time sufficient to attain inert gas equilibrium should have zero IBS independent of other operating parameters. Heat flux, velocity, pressure, geometry, liquid purity (controlled oxide level of 15 ppm), surface condition, pressure-temperature history, inert gas content, temperature ramp and approach to boiling were fixed at values within the range of LMFBR operations.

They ran a series of 5 tests (summary of results presented in Table I). Test A was initially run at steady-state conditions for 30.5 hours, a time estimated long enough to have the sodium in the plenum saturated with the argon cover gas. The results of this test were consistently zero superheats for a series of 26 successive runs. The steady-state operating time between tests was varied and found to have no influence on IBS.

TABLE I. Test Results from France et al.³

Run Number	T _p (°F)	Time From Loop Fill (h)	Maximum Test Section Bulk Superheat (°F)	Incipient Boiling Bulk Superheat (°F)
A.1	900	30.5	0	0
A.2	↑	34.8	↑	↑
A.3		45.8		
A.4		54.3		
A.5		58.3		
A.6		78.7		
A.7		79.7		
A.8		79.8		
A.9		79.9		
A.10		80.0		
A.11		80.1		
A.12		80.2		
A.13		80.3		
A.14		80.4		
A.15		86.0		
A.16		86.1		
A.17		86.2		
A.18		93.7		
A.19		104.2		
A.20		104.4		
A.21		104.5		
A.22		106.8		
A.23		106.9		
A.24		107.4		
A.25		108.4		
A.26	900	108.5	0	0
B.1	900	0.8	120	0
B.2	900	1.5	150	60
C.1	700	34.0	40	20
C.2	700	42.0	100	0
D.1	900	20.0	0	0
D.2	900	20.1	0	0
E.1	700	24.0	30	30

The zero superheat may possibly be attributed to several factors. Flow velocity at boiling was approximately 4.5 ft/sec which is greater than the 4 ft/sec above which the superheat should be zero. However, this effect (as well as other parametric effects) is not independent of the manner in which the test was conducted. No aging effect was noted. Nucleation was suspected to have occurred from gas bubbles in the liquid.

Test B was conducted under the same operating conditions as A, except that B was initially run at steady-state conditions for only 0.8 hours. This procedure affected the inert gas content of the sodium and Test B was performed with less argon dissolved in the sodium. Nucleation in this test was suspected to have occurred from test section wall cavities with a low inert gas partial pressure. There was an increase in superheat from test B.1 to B.2 which is perhaps attributable to a short-term aging effect (i.e., the loss of inert gas from wall cavities).

The results of these two tests suggest that the most significant factor in reducing (or eliminating) superheats is the amount of inert gas present in the system.

Other tests were conducted mimicking pot-type LMFBR conditions. It is not expected that pot-type LMFBR's with a sodium-argon interface several hundred degrees Fahrenheit below the maximum system temperature will consistently exhibit zero superheat at boiling inception independent of system parameters. Thus test series C was conducted using a low plenum temperature (700°F). The other test conditions were the same as for Test A except the steady-state pretest velocity was 13 ft/sec corresponding to a test section heat flux of 5.5×10^5 Btu/h·ft². (Test section inlet and outlet temperatures were 600 and 900°F respectively.) Moderate superheats were obtained for test C.1 after steady-state conditions were imposed for 34 hours. A second test, C.2, conducted 8 hours later, gave a much higher superheat value. As further details of the test were not specified, no explanation was offered for the unusually high superheat of C.2.

Two other tests were performed as controls. Test D was performed under the same conditions as A, and once again yielded zero superheat. Test E was identical to C.1 and moderate superheat values were achieved.

Aberle et al.²⁷ performed sodium boiling tests in a 7-pin bundle under flow rundown conditions. In order to study transient boiling, their test runs simulated a hypothetical sodium boiling accident caused by the loss of electricity to the circulator loops coincident with a failure of the reactor to trip. Some of the parameters had to be preset to specific values so that the axial temperature and pressure profiles shortly before boiling coincided with those calculated for a typical SNR subassembly. These adjustments were necessary as the heated section was only 600 mm in length (compared to a fueled length of 950 mm for the SNR) and the axial power distribution was linear rather than a chopped cosine.

Of the 157 tests performed only 10 are discussed. Table II gives the important operating conditions for these tests. Of the ten tests, only three experienced superheat. These three superheat runs show some similarities in operating conditions: all have low flow velocities at boiling inception and all have low inlet channel to outlet channel pressure drops.

TABLE II. Test Results from Aberle et al.²⁷

Test No. 7-2/		13	14	15	16	17	22	24	25	27	28
STEADY STATE	Channel Outlet Pressure (bar)	1.052	1.052	1.052	1.520	1.053	1.053	1.053	1.053	1.053	1.053
	Channel Inlet Pressure (bar)	3.85	3.88	2.00	4.18	4.00	2.79	2.03	3.80	3.90	2.19
	Pressure Drop (bar)	2.80	2.83	0.95	2.66	2.95	1.74	0.98	2.75	2.85	1.14
	Throttle Valve Setting (1)	C	B	A	B	A	A	A	B	A	D
	Flow Velocity (m/sec)	2.05	3.20	2.10	3.00	4.00	3.11	2.15	3.10	4.02	3.02
	Heat Flux (W/cm^2)	98.2	149.8	98.3	150.3	170.8	153.7	99.3	153.5	177.5	152.6
	Inlet Temperature ($^{\circ}\text{C}$)	563	562	562	562	483	559	553	559	559	559
	Outlet Temperature ($^{\circ}\text{C}$)	723	723	725	735	625	730	715	730	709	730
NUCLEATION	Time Transient Begins t_t (sec)	4.80	2.75	3.75	3.15	2.90	3.40	3.50	3.40	3.70	3.02
	Time Boiling Begins t_B (sec)	13.88	11.85	9.30	12.15	14.15	9.59	9.87	11.42	12.80	3.97
	$t_B - t_t$ (sec)	9.08	9.10	5.55	9.00	11.25	6.19	6.37	8.02	9.10	0.95
	Channel Inlet Pressure at t_B (bar)	1.65	1.72	1.28	2.12	1.48	1.55	1.25	1.82	1.23	1.26
	Mean Rate of Inlet Pressure Change (bar/sec)	-.243	-.235	-.130	-.230	-.224	-.201	-.122	-.247	-.305	Rapid
	Pressure at End of Heated Section at t_B (bar)	1.18	1.24	1.16	1.72	1.20	1.20	1.13	1.21	1.23	1.12
	Total Pressure Drop at t_B (bar)	.60	.67	.23	.60	.43	.50	.21	.77	.18	-
	Flow Velocity at t_B (m/sec)	.76	1.4	.42	1.13	1.12	1.41	.33	1.48	1.70	0
	Superheat ($^{\circ}\text{C}$)	0	0	22	0	0	0	68	0	0	27
BOILING	Length Equivalent Void $t_B + 1$ (mm)	55	125	not	115	135	115	not	120	150	310
	Length Boiling Region $t_B + 1$ (mm)	140	220	com-	215	240	210	com-	205	300	600
	Length Equivalent Void $t_B + 1.5$ (mm)	130	285	par-	265	355	440	par-	290	470	465
	Length Boiling Region $t_B + 1.5$ (mm)	300	445	able	425	545	560	able	420	590	800
	Lower Interface Reaches 300 mm (sec+ t_B)	2.28	2.03	"	1.97	1.56	1.63	"	2.15	1.72	0.54
	Upper Interface Reaches 850 mm (sec+ t_B)	1.65	1.42	"	1.52	1.46	1.37	"	1.45	1.20	1.62
	Flow Reversal Begins (sec+ t_B)	2.32	1.85	.04	1.80	1.33	1.43	.01	2.06	1.53	-
	Dryout Begins (sec+ t_B)	2.62	2.09	0.89	1.98	1.38	1.51	.57	2.25	1.75	1.96
	Equivalent Film Thickness (mm) (based on heat flux and time to dry out)	0.90	1.08	0.31	1.03	0.81	0.81	0.20	1.24	1.07	1.03
	Power Off (sec+ t_B)	2.62	2.00	0.69	2.06	1.57	2.08	1.34	2.69	2.02	2.27
	Boiling Ceases (sec+ t_B)	4.98	4.30	1.76	4.12	3.39	5.37	5.75	6.63	5.24	19.6

(1) A - fully open, no throttling B - intermediate C - almost closed, high throttling D - closed

An interesting phenomenon to note is the different flow regimes obtained between the superheated and non-superheated runs. The authors discovered that close to the lower boiling interface there is a region in which vapor and liquid are mixed as a virtually homogeneous mixture. Those runs exhibiting no superheat were the clearest examples of this behavior. Moderate superheat runs exhibited these two-phase regions to a lesser extent whereas the 68°C superheat run showed a more marked steplike transformation from vapor to liquid.

Sodium boiling tests on a 19-pin simulated fuel assembly were conducted at ORNL²⁸ to investigate the extent of boiling stability at low-flow conditions. Test procedure was to establish the flow necessary to give a specific test section bulk temperature of 700°C, decrease flow to a low value and hold there for a prescribed period of time (dwell time). Dwell time (between 20 and 90 seconds) was a compromise between approaching steady-state and avoiding excessive loop temperatures between the test section and the expansion tank. At the end of the dwell period flow was increased so as to give a test-section outlet temperature of 540°C. Test section flow during dwell was preset to produce test-section temperatures near saturation or to produce various intensities of boiling.

Of approximately 60 flow transients conducted, about half culminated in boiling and 5 were continued into dryout. Six tests were outlined in this report, all of which experienced some degree of superheating. Some test details are provided in Table III.

This data roughly exhibits the velocity effect noted earlier, although there is insufficient data and considerable scatter.

Table III. Selected Results for 19-Pin Bundle Boiling Tests Performed at ORNL²⁸

Test Number	55A Run 101	71F Run 101	71H Run 101	72A Run 101	72B Run 101	73E Run 102A
Heater Power per Pin (kW)	4.1	6.3	6.7	9.7	10.0	15.3
Time Low Flow Established, t_{lf} (s)	7.5	8.5	7.7	9.1	8.3	9.0
Time Boiling Begins, t_b (s)	44.1	15.8	14.2	15.1	13.0	10.4
$t_b - t_{lf}$ (s)	36.6	7.3	6.5	6.0	4.7	1.4
<u>Conditions at t_b</u>						
Inlet Temp. (°C)	382	390	386	383	387	450
Ch. Inlet Pressure (bar)	1.60	1.60	1.61	1.68	1.70	2.28
Ch. Outlet Pressure (bar)	1.34	1.31	1.32	1.38	1.38	1.83
Total Pressure Drop (bar)	0.26	0.29	0.29	0.30	0.32	0.45
Flow Velocity (m/s)	0.23	0.33	0.36	0.70	0.70	1.5
Superheat (°C)	~28	44	8-10	50	19	<5

There is a difference in superheats between tests 71F (44°C superheat) and 71H (5-10°C superheat) and tests 72A (50°C superheat) and 72B (19°C superheat) for almost equivalent flow velocity and pressure drops. The reason for this is unclear, since detailed operating procedures were not documented. Perhaps these variations are within normal data scatter, or perhaps some unspecified operating condition was varied. The flow velocities at boiling inception were generally lower than those non-superheated runs of Aberle et al. and roughly correspond to flow velocities for the superheated runs.

A possible explanation for the degree of superheat and the scatter could be the system cleanliness. These tests were performed under a clean system with oxide concentration kept below 10 ppm. (Oxide level for France et al.³ was kept at 15 ppm.) Inert gas concentration was not specified, and as this is a key system variable its omission makes analysis of this data difficult.

It would be interesting to find out if all 60 runs experienced superheating, and if not, what test conditions were followed for the non-superheating runs. Although the superheat values obtained were within the probable ranges set by Kottowski and Savaterri¹ for a technically clean system, it is nonetheless worthwhile to determine why they consistently obtained superheats whereas other experimenters operating under LMFBR mock up conditions found none.

III. CONCLUSIONS

Experimental superheat data reported from different laboratories are often contradictory as shown by the data presented in this survey. However, inert gas concentration is generally agreed to be a very significant parameter. It has been postulated to be responsible for the heat flux and velocity effects. Unfortunately, very few investigators control or measure the inert gas concentration and thus its true effect is still not known. Oxide concentration is also seen as an important variable. Heat flux and rate of temperature rise show the least experimental agreement and are the least understood effects. More experimental work needs to be done to see if heat flux and rate of temperature rise are really independent variables or if their observed effect is actually due to variations in some other system parameter.

Superheats from experiments performed simulating LMFBR conditions all fell within the average superheats specified by Kottowski and Savatterri.¹ France et al.³ achieved zero superheat in their experimental system with a sufficient amount of inert cover gas. As neither Aberle et al.²⁷ nor the ORNL²⁸ experiments specified inert gas concentration, it is unclear whether low inert gas concentrations were responsible for the superheats observed. Further experiments performed simulating LMFBR conditions should control and measure the inert gas concentration.

Kottowski and Savatterri¹ postulate that there is a characteristic range of superheat values which is not exceeded for a given set of operating conditions. Heating surface finish, oxide level, and gas loading of the sodium are believed to determine the characteristic range. A conservative estimate for threshold superheat is given by Leonev and Prisnyakob (Reported in Ref. 1) as:

$$\Delta T = 485 - 0.71 (T_s - 500) \text{ } [^{\circ}\text{C}],$$

where T_s is the saturation temperature [$^{\circ}\text{C}$].

In conclusion, superheat data is not conclusive enough to be able to predict superheats for a given set of operating conditions.

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APPENDIX

Summary of Several Sodium Incipient Boiling Experiments*

Schultheiss⁷:

Parameters studied: test surface material, geometry of an artificial cavity, sodium oxide concentration.

Experimental equipment: pool boiling, polished stainless steel with artificial cylindrical cavity 0.4 mm in diameter, 0.2 mm in depth.

Method of achieving boiling inception: increasing temperature in the cavity area by means of hot finger heating system.

Operating conditons:

heat flux	~20 W/cm ²
system pressure	not specified
bulk superheat	-
oxygn concentration	less than 0.3 ppm

No inert cover gas used.

Logan et al.⁹:

Parameters studied: velocity, heat flux, oxygen concentration, surface conditions.

Experimental equipment: single-channel, smooth stainless steel.

Method of achieving boiling inception: steady-state: hold pressure, flow rate, inlet temperature constant, increase power to heater uniformly to onset of boiling (~40 sec). Flow coastdown: hold pressure, inlet temperature and heater power constant, uniformly decrease flow rate to onset of boiling (~25 sec).

Operating conditions:

heat flux (Btu/h·ft ²)	200,000 - 540,000
system pressure (psia)	4.5 - 6.6
velocity range (ft/sec)	3.0 - 8.9
Reynolds number range	27,000 - 80,000
bulk superheat (°F)	-20 - 130
wall superheat (°F)	20 - 170
oxygen concentration (ppm)	1 - 5

No measure of inert gas concentration.

*Other experimenters did not provide sufficient data to fully characterize experiment.

Kikuchi et al.²²:

Parameter studied: flow rate.

Experimental equipment: sodium boiling test loop SIENA with sheath-type heater pin test section.

Method of achieving boiling inception: hold flow rate and inlet temperature fixed, increase heat flux gradually to point of boiling inception.

Operating conditions:

heat flux (W/cm ²)	62 - 177
Na velocity (m/s)	0.27 - 2.86
inlet temperature (°C)	376 - 704
Ar gas pressure (kg/cm ² ·G)	0.01 - 0.1
wall superheat (°C)	9-69
Oxygen concentration (ppm)	<5

Cover gas-high purity argon with combined oxygen and water content held below 5 ppm.

Kikuchi and Haga¹⁶:

Parameters studied: temperature ramp.

Experimental equipment: Same as above.

Method of achieving boiling inception: hold pressure, inlet temperature, heat flux constant. Reduce flow rate by:

- 1) pump coastdown method: flow rate decreased with decreasing pump power
- 2) sudden pump stop method: flow rate rapidly reduced with switching off the pump power
- 3) valve closure method: closed sodium entrance valve.

Operating conditions:

heat flux (W/cm ²)	32 - 139
flow velocity at boiling inception (m/s)	0 - 0.65
inert temperature (°C)	352 - 424
gas pressure (bar)	1.09 - 1.16
wall superheat (°C)	~ 41° - 149

No mention of oxygen concentration or inert gas concentration.

Dwyer et al.:^{14,15}

Parameters studied: heat flux, velocity, operating time.

Experimental equipment: polished stainless steel annular channel.

Method of achieving boiling inception: maintain heat flux and flow rate constant and increase inlet temperature at fixed rate of 0.7°F/min.

Operating conditions:

heat flux (Btu/h·ft ²)	25,000 - 300,000
static pressure (psia)	3.9
velocity range (ft/s)	0.24 - 1.4
Reynolds number range	3,900 - 23,000
wall superheat (°F)	40 - 180°F
oxygen concentration (ppm)	~5