

Liquid Nitrogen Flashing in the glass vessel under Rapid Depressurizations

**T Watanabe^{1*}, A Nakano¹, K Tokunaga¹,
T Shiigi¹, K Shiimojima²**

1. National Fisheries University, Japan

2. Okinawa National College of Technology, Japan

ABSTRACT

Recently, a demand for cryogenic fluids as a coolant has been increasing because of the industrial development of low temperature technology. The purpose of this study is to clarify some fundamental features of the phase changes associated with the flashing of cryogenic fluid. Liquid nitrogen at low temperatures was used as the test liquid. Experiments on the decompression boiling of liquid nitrogen in a pressure vessel made of glass were conducted. In these experiments, many types of boiling behavior were observed. These were classified into several typical patterns by visual observation. The degree of superheat of liquid nitrogen at the start of boiling was found to depend strongly on the rate of depressurization.

1. INTRODUCTION

The use of cryogenic fluids is increasing because of the advance of super-conductive device technology, aerospace engineering, cryogenic medical treatment and food processing techniques. Therefore, in order to establish safety technology for cryogenic systems, fundamental features of violent phase changes associated with the storage management of liquefied gas must be clarified. Cryogenic fluids are usually stored at high pressure and the phenomenon of violent boiling under these conditions is therefore of special interest. This violent boiling, better known as the flashing phenomenon, has been studied extensively, in relation to loss-of-coolant accidents (LOCA) in nuclear reactors. Therefore, most of the studies are limited to the condition of high-pressure and/or high-temperature for water [1-9]. However, the effect of slow depressurization rates on this phenomenon and the occurrence of the phenomenon in other fluids have not been investigated sufficiently. The main feature of the flashing phenomenon in cryogenic fluids is that boiling starts at the wall surface of the pressure vessel and/or pipeline where the temperature of the liquid in contact is higher due to heat transfer from the environment. Usually, liquids of lower boiling point possess lower values of the latent heat of vaporization, viscosity and surface tension. These liquids have a tendency to readily start boiling. This fact suggests that nucleation at the wall surface of the vessel and/or pipeline is predominant in cryogenic fluids. In the flashing of cryogenic liquids, therefore, existence of bubble nuclei at the wall greatly affects the flashing pattern and pressure changes in the vessel.

The authors conducted flashing experiments with liquid nitrogen from a low temperature technological point of view [10-12]. In those studies, we discussed the following effects on the flashing phenomena; thermal stratified layer in the liquid, the rate of depressurization, the initial liquid temperature, the minimum pressure, and mist formation above the vapor-liquid interface under rapid depressurization rates.

*Corresponding Author: watanabe@fish-u.ac.jp

In the previous paper, the effect of surface roughness of the vessel on the flashing phenomena was reported [13]. Various flashing patterns, including delayed type, were obtained in the case of glass vessel. The authors, therefore, conducted many additional experiments in order to clarify the characteristics of flashing in a glass vessel.

The purpose of this paper is to describe the flashing behavior of liquid nitrogen in a glass vessel in more detail.

2. EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus is illustrated schematically in Figure 1. The apparatus consists of a cryostat (pressure vessel and vacuum jacket), a vacuum pump, a liquid nitrogen tank, and measuring systems. The pressure vessel is made of glass and is 184mm in length and 27.0mm in inner diameter. For thermal insulation the vessel was jacketed in a larger glass vessel, 270mm in length and 90.4mm in inner diameter. To control the rate of depressurization, an orifice of variable size was mounted on top of the pressure vessel. A pressure transducer was set on an upper flange at the top of the glass vessel. Three copper-constantan thermocouples with SUS-316 sheathing of outer diameter 0.5mm were set in the pressure vessel.

To maintain a high level of thermal insulation, the vacuum jacket was evacuated to the order of 10^{-4} Pa. Liquid nitrogen was supplied from a reservoir tank to the pressure vessel. After the vessel was filled with the desired amount of liquid nitrogen, the initial pressure inside the vessel was set to a prescribed level by means of self-pressurization (150-550kPa). The flashing experiment was then initiated with the rapid breaking of a rupture film. This results in a sudden release of gaseous and liquid nitrogen from the vessel. The measurement of pressure was triggered by the valve-opening signal, and the data was logged and processed by a personal computer in on-line mode. The explosive boiling behavior caused by the depressurization was recorded by a video camera.

The range of the depressurization rates was from 0.10 to 10.00MPa/s.

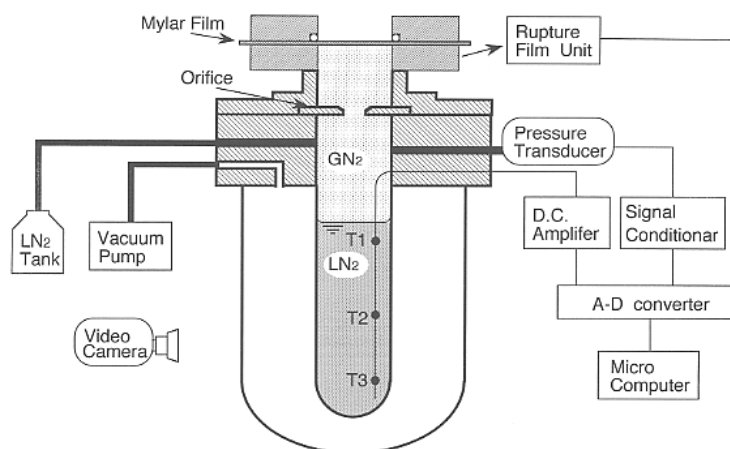


Figure 1: Schematic diagram of experimental apparatus

3. RESULTS AND DISCUSSIONS

3.1. Initial Temperature Distributions in Liquid Nitrogen

In a cryogenic liquid stored in a reservoir, there exist vertical and radial differences of temperature in the liquid as a result of heat transfer from the environment. Figure 2 shows the temperature change in the liquid nitrogen in the period of self-pressurization. In this figure, the symbol at the top describes the saturation temperature corresponding to the pressure in the vessel, and remaining symbols represent measured temperatures in the liquid nitrogen. As time proceeds, the liquid temperature increases and reaches its highest value at the top of the liquid. Comparison between saturation temperature corresponding to the pressure in the vessel and the measured liquid temperatures indicates that whole of the liquid is in subcooled state. This situation is the same as in the case of a metal vessel [13]. In the glass vessel, however, there were several cases where the pressurization suddenly finished by an unexpected boiling. Figure 3 shows the temperature distributions for such a case. The temperature T_1 , upper most in the liquid, is lower than saturation temperature corresponding to the pressure in the vessel. This result shows the existence of superheated liquid. This state is dangerous from the viewpoint of safety management, because the liquid possesses higher thermal-energy than that in an equilibrium or subcooled state under the same pressure. The occurrence of such a superheated situation was observed in 16 runs in a total of 102. These 16 runs were excluded from the classification of flashing patterns in the following section.

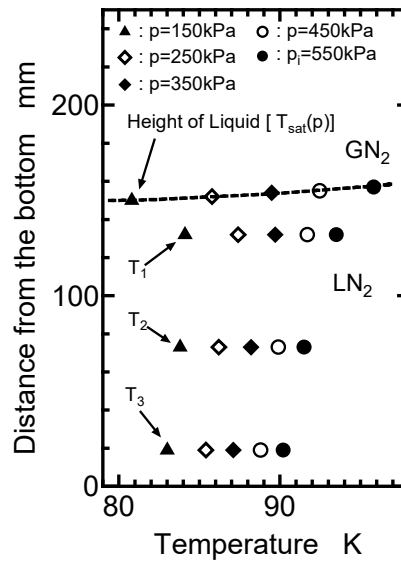


Figure 2: Temperature change in LN_2 in the period of self-pressurization (without pre-boiling)

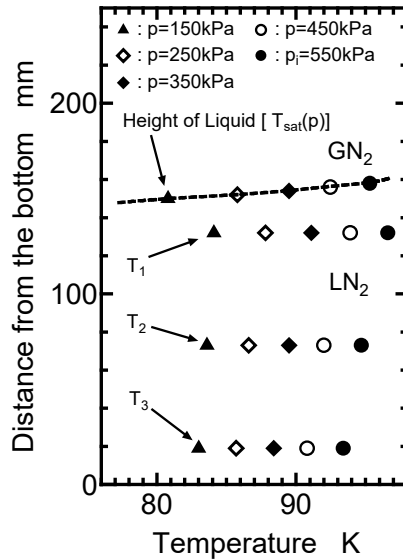


Figure 3: Temperature change in LN_2 in the period of self-pressurization (with pre-boiling)

3.2. Classification of Flashing Patterns

Flashing experiments were carried out under the following conditions: initial pressure $p_i = 350, 400, 450, 500, 550$ kPa, initial height of liquid $H_i = 155$ mm, and orifice diameter $d = 1, 3, 5, 10, 15, 20$ mm. In each experiment, video images of the flashing behavior and pressure data were recorded for ten seconds from the beginning of depressurization. Observed results were difficult to be interpreted, because several flashings appeared under the same initial conditions. To understand these stochastic phenomena, we tried to classify the boiling behavior into four typical flashing patterns. These are as follows:

- <Type1>: After starting the depressurization, boiling occurs only in the region nearby the upper surface of the liquid. The boiling continues quietly for a long time and remains at the same location without proceeding downwards through the liquid.
- <Type2>: Boiling, initially generated underneath the vapor-liquid interface, proceeds towards the bottom of the vessel as time progresses. Propagation of the boiling front is continuous.
- <Type3>: In the early stage of depressurization, boiling behavior is the same as the Type1 or 2. But in the succeeding period of time, other bubbles are generated and activated at the middle or lower part of the liquid.
- <Type4>: Boiling occurs simultaneously at both the top and bottom regions of the liquid column, and individual bubbles grow up explosively in the whole liquid. After a while these bubbles collapse at once throughout the liquid phase.

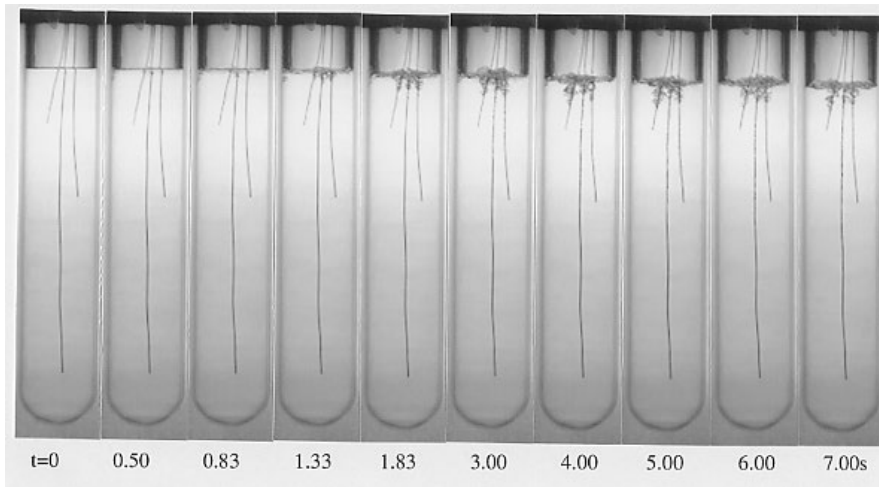


Figure 4: Photographs of the boiling Type1, ($d=1\text{mm}$, $p_i = 559.9\text{kPa}$, $\Sigma_{max}=0.50\text{MPa/s}$)

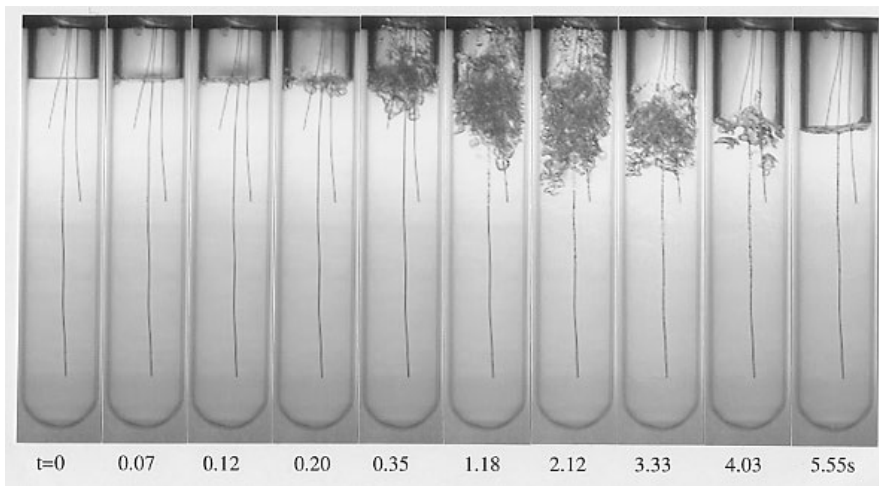


Figure 5: Photographs of the boiling Type2, ($d=3\text{mm}$, $p_i = 546.2\text{kPa}$, $\Sigma_{max}=4.60\text{MPa/s}$)

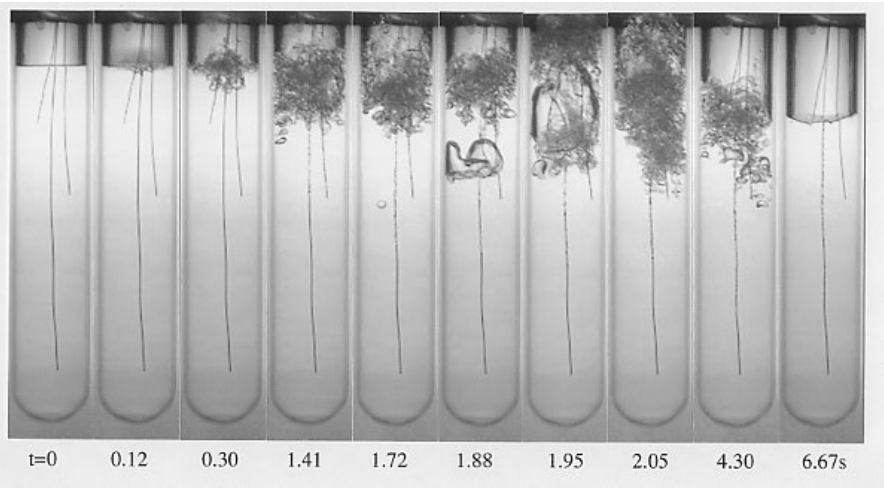


Figure 6: Photographs of the boiling Type3, ($d=3\text{mm}$, $p_i = 558.7\text{kPa}$, $\Sigma_{max} = 4.80\text{MPa/s}$)

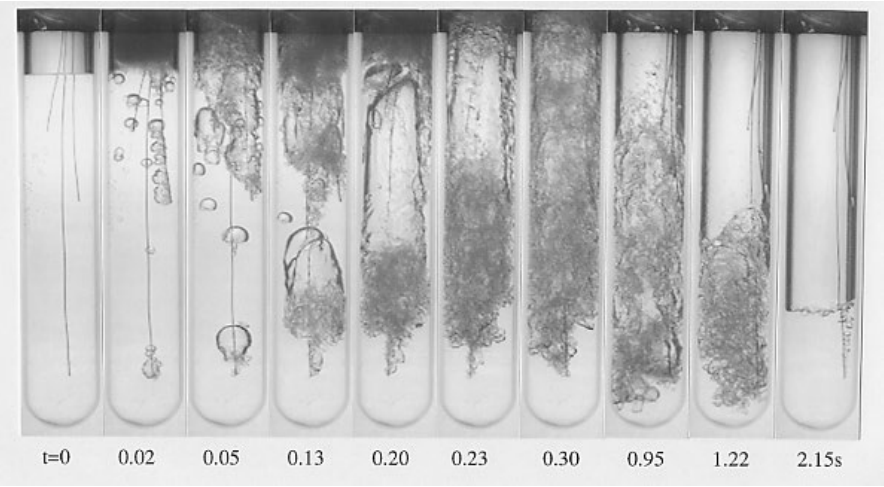


Figure 7: Photographs of the boiling Type4, ($d=10\text{mm}$, $p_i = 556.2\text{kPa}$, $\Sigma_{max} = 10.30\text{MPa/s}$)

Table 1: Classification of flashing patterns

p_i kPa d mm	350	400	450	500	550
1	③	③	③	②③	①②
3	③	③	③	③	②③
5	①③	②③	①②③	③	②③④
10, 15, 20	④	④	④	④	④

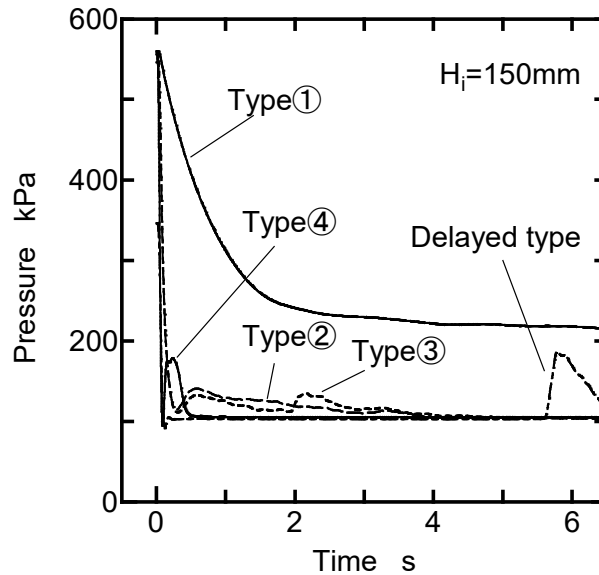


Figure 8: Pressure-time histories of various boiling types

The photographs of these typical boiling types, Type1 through Type4, are shown in Figures 4-7, respectively. Table 1 shows the classification of flashing patterns for various combinations of the orifice diameter and the initial pressure in the vessel. In Figure 8, pressure-time histories in the vessel are indicated for all of the boiling types. Each boiling type is correlated with the pressure change as follows. Flashing Type1 occurs with the least frequency in all the experiments. Since boiling is limited to the region near the vapor-liquid interface, there is no pressure increment due to the small amount of vapor generated. So the pressure in the vessel decreases monotonously to the atmospheric pressure with the lapse of time. In the case of Type2, vaporization of the liquid is affected by the propagation velocity of the boiling front that penetrates into the liquid from the vapor-liquid interface. Bubbles do not grow larger and so the pressure changes irregularly without the characteristic peaks that would indicate pressure recovery. Type3 occurs under all initial conditions except for the case of extremely rapid depressurization. The growth of the bubbles appearing at the middle or lower part of the liquid has an immediate effect on the recovery of pressure. Type4 is observed in the condition of extremely rapid depressurization with high reproducibility. In this case, the boiling starts from the surface of thermocouples and bubbles grow explosively in the whole liquid. Then, a large amount of vapor is generated in a short period. This results in a high peak value of the pressure recovery.

In the case of metal vessel, the typical flashing pattern is that the boiling, initially generated at the vapor-liquid interface, proceeds continuously through the liquid to the bottom of the vessel [13]. In the glass vessel, on the other hand, other types of discontinuous boiling are obtained. In such irregular cases, boiling occurs independently at the middle or the bottom of the liquid in addition to the boiling starting from the vapor-liquid interface. In this case, there exists a non-boiling liquid region in between the two boiling zones.

A curious phenomenon was also observed in the glass vessel. Boiling did not occur in a depressurized process and the pressure decreased to the atmospheric pressure. Then, a few seconds after, under the same atmospheric pressure, boiling started suddenly. Photographs of such a peculiar boiling process are shown in Fig.9 and the corresponding pressure change is represented in Fig.8. Although the pressure in the vessel reduced to the atmospheric pressure ($t=0.2$ seconds), no distinct boiling happened, but about five seconds later, sudden boiling started which led to the rapid increase in the pressure.

The pressure-time history shows that the boiling from the middle or lower part of the vessel strongly affects the pressure change in the vessel. The variety of flashing patterns in the glass vessel, compared to those in the metal vessel, suggests that these stochastic boiling phenomena are strongly related to the number of nucleation sites and/or defects on the wall of the glass vessel.

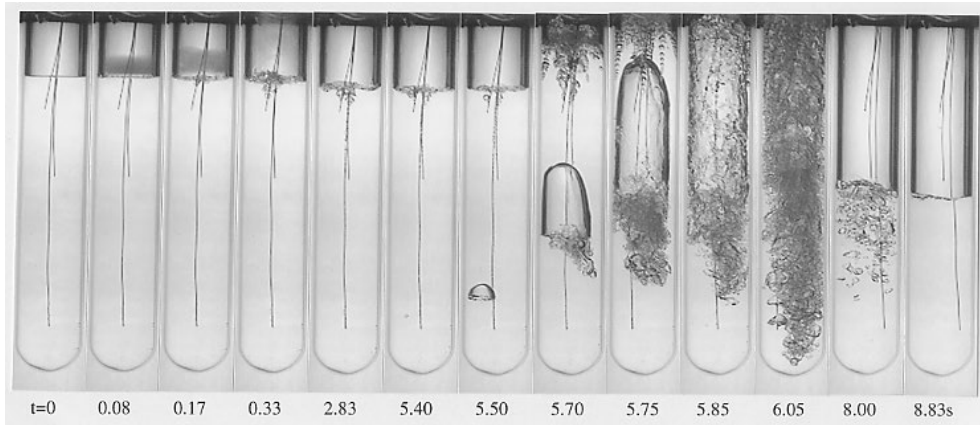


Figure 9: Photographs of delayed-boiling type, ($d=5\text{mm}$, $p_i = 346.1\text{kPa}$, $\Sigma_{max} = 4.70\text{MPa/s}$)

3.3. Limits of Superheat and Rates of Depressurization

As mentioned above, the boiling generated in the middle or lower part of the liquid contributes greatly to the increase in pressure of the vessel. We shall examine under what conditions this boiling takes place. We can evaluate the superheat of the liquid at the start of boiling by using pressure-time histories and recorded video images of the flashing experiment. The maximum superheat of the liquid is defined as $(\Delta T_{sat})_{max} = T_a - T_b$, where T_a is liquid temperature nearby the location where the boiling starts, and T_b is the saturation temperature corresponding to the pressure at the beginning of the boiling. Figure 10 represents the relationship between the maximum superheat and the rate of depressurization Σ_{max} . This figure shows that, when the orifice diameter is less than 5mm, the values of the maximum superheat are around 10K and have a tendency to slightly increase with increasing rate of depressurization. In the case of a larger orifice, say 15 to 20mm in diameter, i.e., in a higher depressurization rate, the superheat of the liquid was evaluated as about 0K. The data for an orifice of diameter 10mm falls between those for smaller orifices and larger ones.

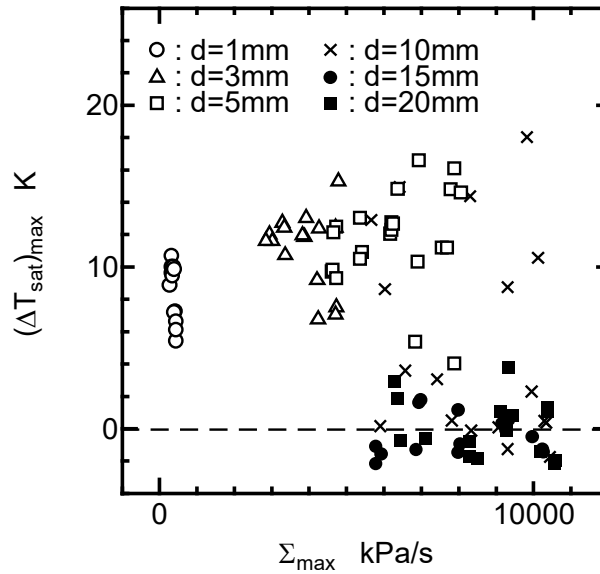


Figure 10: Maximum superheat of the liquid versus rate of depressurization

The results show that the heterogeneous nucleation on the metal surface becomes predominant at a high rate of depressurization. In these experiments, only boiling Type4 was observed at high depressurization rates. Whenever it happens, the boiling starts from the surface of thermocouple as shown in Figure 7. In the previous paper, we mentioned that there exist more cavities on the metal wall more than that on a glass wall [13]. Therefore, the result that $(\Delta T_{sat})_{max}$ decreases to 0K can be considered to correspond to the transition from the boiling in the liquid to that on the surface of thermocouples at the middle or bottom-part in the vessel.

CONCLUSIONS

To study the fundamental features of flashing phenomenon of cryogenic liquid, flashing experiments under depressurized conditions have been conducted on liquid nitrogen in a glass vessel. The obtained conclusions can be summarized as follows.

- 1) Various flashing patterns were observed in a glass vessel. In all of the patterns obtained, boiling starting at the middle or lower part of the vessel has strong effect on the pressure changes in the reservoir.
- 2) In a condition of relatively low depressurization rate (less than 5MPa/s), there is a tendency for the maximum superheat of the liquid to increase with increasing rate of depressurization. At much higher rate of depressurization, the boiling occurs more readily from the metal wall as a result of predominant heterogeneous nucleation.

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