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Drop-Size Estimates for a Loss-of-Coolant-Accident

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NOMENCLATURE AND DIMENSIONS

B	$\equiv \dfrac{T_\ell - T}{T_\ell}$	None
C	- bubble growth-rate constant	$m/s^{1/2}$
C_ℓ	- liquid specific heat	J/kg/K
d	- drop diameter	m
D	- diameter of bubble, jet, orifice, or break	m
G_B, g_B	- see Appendix C	None
ℓ	- pressure zone length	m
L	- latent heat of vaporization; length	J/kg;m
M	- mass	kg
N	- number of drops per bubble burst; nucleation density per unit volume	None;$1/m^3$
n	- wall surface nucleation density per unit area; number of drops	$1/m^2$;None
P	- pressure	Pa
$\hat{q}$	- maximum heat transfer flux	W/m^2
q	- heat transfer flux	W/m^2
T	- temperature	K
ΔT	- superheat temperature	K
U	- velocity	m/s
We	- Weber number = $\rho_g U^2 d/\sigma$	None
X	- quality	None
α_ℓ	- liquid heat diffusivity	m^2/s
α	- void fraction	None
δ	- film thickness	m
ρ	- density	kg/m^3

NOMENCLATURE AND DIMENSIONS (cont)

σ	- surface tension	N/m
θ	- time	s

Subscripts

v	- vapor
ℓ	- liquid
g	- gas
j	- jet
b	- bubble
m	- maximum
1,2	- locations

DROP-SIZE ESTIMATES FOR A LOSS-OF-COOLANT-ACCIDENT

by

A. Koestel, R. G. Gido, and D. E. Lamkin

ABSTRACT

Drop sizes ranging between 16 and 76 μm are estimated for loss-of-coolant-accident (LOCA) conditions. A break size diameter of 0.3 m (1 ft.) and liquid temperature of 590 K (600°F) are assumed. The best estimate is that the drop size will be less than 16 μm due to the combined effects of heterogeneous and homogeneous nucleation and of aerodynamic atomization. The calculations are based on an extrapolation of available low-temperature fragmentation data to typical LOCA conditions. The extrapolation is supported by a semiempirical fragmentation model that is consistent with low-temperature measurements reported in the literature. If drops are formed by some unknown process upstream of the break, the largest drop that can escape fragmentation when passing through the break opening is estimated to be 46 μm.

I. INTRODUCTION

The objective of this report is to estimate the water drop sizes produced in the effluent from a hypothetical LOCA of a pressurized water reactor (PWR). This is a matter of interest in the determination of the pressure-temperature history of the postaccident containment atmosphere because the retention time of liquid water drops in the atmosphere may be drop-size dependent.

No data that are directly applicable were found in the literature. However, five publications were found dealing with the formation of drops by fragmentation of superheated water jets and by bursting air bubbles in water.[1-5] The maximum temperature of the water encountered in these papers was approximately 420 K (300°F) and the ambient pressure ranged from 0.1 MPa (one atmosphere) to a vacuum of 0.3 kPa. It thus became necessary to devise a reasonable means of extrapolating from the available data to LOCA conditions. The basic approach used was to construct a semiempirical mechanistic model for jet fragmentation that is consistent with available data and then to extrapolate this model to LOCA conditions.

Because the extrapolation involved is great and the mechanisms involved are poorly understood, the results are not substantive. Perhaps, however, by varying some of the key assumptions, bounding values of the drop size can be estimated.

II. DISCUSSION

The dispersion of liquid in bulk form into drops can be accomplished by

1. aerodynamic forces acting on the liquid surface (atomization where the drop size so formed is a function of the Weber number), or
2. thermal fragmentation of a liquid in a superheated state.

Thermal fragmentation is a result of vapor bubbles extending the liquid into thin films that, upon rupture, form many small drops. Both dispersion processes result in a process of the opposite character, namely "drop coalescence," which tends to return the liquid dispersion to bulk form. In estimating the drop sizes caused by a LOCA, all three processes should be considered (aerodynamic atomization, thermal fragmentation, and coalescence).

The empirical correlation in Ref. 1 implies that both aerodynamic and thermal forces are factors in determining drop size because the drop diameter is a function of the nozzle Weber number and the liquid supply temperature. In Ref. 2, the experimentors purposely held the Weber number at a low value so that the aerodynamic effect could be assumed negligible. Their correlation showed the drop diameter to be a function of the nozzle diameter and the supply temperature. A similar dependency was presented in Ref. 3. Also, a test was described using a heated and unheated liquid jet with the surface tension and supply pressure both held constant. The results showed a rapid breakup at the nozzle for the heated jet whereas the unheated jet had an extended undispersed portion. This observation suggests that, for a superheated jet, the thermal fragmentation process is more rapid than aerodynamic atomization and is the controlling process.

We establish limits in the following two sections by estimating drop sizes resulting from (a) aerodynamic atomization alone and (b) thermal fragmentation alone. In addition, a third estimate is made of drop size based on an empirical equation from turbine technology.

Reference 3 describes tests showing that droplets in a state of surface vaporation can repulse each other and that coalescence is thereby hindered. Because the drops formed in a LOCA will be superheated, coalescence is neglected here.

A. Jet Breakup by Aerodynamic Atomization

A criterion for determining the breakup of drops is the Weber number[6]

$$We = \frac{\rho_g U^2 d}{\sigma} ,$$

where ρ_g and U are the surrounding medium (gas) density and velocity, respectively; d is the resulting liquid drop diameter; and σ is the liquid surface tension. Minimum Weber number values of 12 (Ref. 6) and 20 (Ref. 7) are recommended. The resulting drop sizes are thus readily estimated.

To estimate drop sizes, assume

1. $\rho_g = 1.6$ kg/m^3 (air density at atmospheric conditions),
2. $\sigma = 0.06$ N/m [water surface tension at 373 K (212°F)], and
3. U = 146 m/s [an approximate value for the critical velocity resulting from the blowdown of saturated water at 554 K (520°F) based on Ref. 8].

Drop sizes of 21 and 35 μm result for Weber numbers of 12 and 20, respectively.

B. Jet Breakup by Thermal Fragmentation

The proposed model to estimate drop sizes formed by thermal fragmentations requires knowledge of the bubble nucleation population and the maximum size before bursting. This defines the total amount of surface energy created by bubble growth. By making the far-reaching and limiting assumption that the surface energy is conserved during fragmentation, drop size can be computed by introducing liquid mass conservation.

Conservation of surface energy is an assumption requiring some support. This is a limiting-type assumption because some loss of free energy is required for the process to occur. However, the loss may not be too great. For example, it can be shown that when drops are formed from a liquid ligament (Rayleigh instability), approximately 20% surface energy will be lost. This question is further addressed in Appendix A where the conservation of liquid mass and surface energy assumptions are used to examine drop measurements from bursting bubbles as reported in Refs. 4 and 5. The agreement is found to be reasonable, thereby substantiating the assumption that surface energy is approximately conserved.

If the creation of surface energy due to bubble expansion in a superheated liquid could proceed to thermodynamic equilibrium, the problem of computing drop size would be simplified. However, experiments indicate that fragmentation can occur before reaching equilibrium and that the drops so formed are superheated and will finally reach thermal equilibrium by surface evaporation. According to Brown and York,[1] the condition at the point of fragmentation is unique and reproducible. Their data show little gain in jet breakup by further increases in the supply temperature. Measurements in Ref. 9 support this contention.

If the bubble expansion process proceeds to a unique value of the void fraction, then the resulting theoretical equation can be tested with experimental data. This is shown in Appendix B. Reference 1 correlates a bubble growth-rate constant and a Weber number based on the jet diameter (We_j) evaluated at the point of jet breakup in the following form. For $We_j < 1.25$,

$$C = 0.10 - 0.0030\ We_j\ ,$$

and for $We_j > 12.5$,

$$C = 0.058 - 0.0021\ We_j\ ,$$

where

$$C = \left[\frac{C_\ell (T_\ell - T)}{L}\right] \left(\frac{\rho_\ell}{\rho_v}\right) (\pi\ \alpha_\ell)^{1/2}\ .$$

Note that the product of the first two parenthetical quantities in the definition of C is the volumetric increase upon flashing, and α_ℓ is the thermal diffusivity of the liquid.

The empirical correlation above reveals two limiting conditions. When We_j equals zero and C equals 0.10 $m \cdot s^{-1/2}$, the atomization effect is negligible. When C equals zero, fragmentation due to bubble expansion is negligible and aerodynamic atomization is controlling. Therefore we must determine what breakup mechanism might be controlling at large-scale, high-temperature LOCA conditions. Tests described in Ref. 3 show that the atomization rate is much slower than that of thermal fragmentation; therefore, we can assume that thermal breakup dominates and that we should use a value of $C = 0.10\ m \cdot s^{-1/2}$ in computing the void fraction at the point of dispersion.

Another experimentally determined criterion for predicting the point of thermal fragmentation is presented in Ref. 9. Values of the quantity

$$B = \frac{T_\ell - T}{T_\ell}\ ,$$

where $0.07 < B < 0.1$, are given for breakup conditions over a wide range of ambient pressures (0.1 MPa to 0.3 kPa). Values of B are introduced into the drop-size formulation in Appendix B. Both values of B and C are required in the deviation because a state of nonthermodynamic equilibrium exists at the point of jet breakup.

The estimation of bubble population density for heterogeneous and homogeneous nucleation is another significant phenomenon that requires limiting-type considerations. Heterogeneous nucleation implies that bubbles formed on the nozzle or on the break opening surface are subsequently entrained into the bulk of the flowing liquid. In homogeneous nucleation, the bubbles are formed within the liquid bulk. Liquid temperatures near the critical point are required for homogeneous nucleation according to Ref. 10. This reference gives experimental indication that water between 530 and 590 K (550 and 600°F) can experience homogeneous nucleation during pressure reduction. Appendix B presents methods for estimating bubble population or nucleation density for both heterogeneous and homogeneous nucleation. Both are considered separately at LOCA conditions to identify a range of drop-size estimates. The actual drop size expected should be greater than either because the effects are probably additive at the LOCA temperature level.

The thermal fragmentation model described in Appendix B yields Eq. (B-5), which becomes Eq. (B-8) for heterogeneous nucleation, for comparison with test data in Fig. B.5. The agreement is good within the temperature range of the data, 310-420 K (100-300°F). Drop sizes for homogeneous nucleation are also computed in Appendix B based on the high-temperature bubble count data (Fig. B.3) from Ref. 11.

C. Maximum Size Drop That Can Escape Fragmentation as Determined from Turbine Technology

Under certain conditions, two-phase flow can occur upstream of the break opening. Assuming that drops are formed by some other process in the upstream high-pressure chamber, the maximum size of drop that will not flash or fragment when flowing from high to low pressure through the break can be estimated. This is accomplished via an empirical equation valid for the flow of wet steam and used in steam turbine technology for estimating the maximum drop size that can escape flashing when experiencing a pressure reduction from P_1 to P_2 during a time interval of $\Delta\theta$. The equation is from Ref. 7 and presented in Appendix C where it is applied to a pressure reduction zone extending a certain distance downstream from the orifice face. The zone length is estimated to be of the order of the orifice diameter, and the time interval is then equal to D/U where U is the flow velocity and D is the break diameter. For a pressure ratio equal to 2 and a flow velocity of 146 m/s (480 ft/s), through an orifice of 0.3 m (1 ft.) in diameter, the maximum drop size that can escape flashing is calculated to be 46 μm (see Appendix C). For pressure ratios greater than 2 the flow velocity will be greater but the pressure reduction zone length will also increase (Ref. 12) and it is possible that the drop size will change only minimally.

III. SUMMARY OF RESULTS

Table I presents the results of drop-size calculations for LOCA conditions based on the three limiting conditions,

1. thermal fragmentation due to heterogeneous nucleation at the walls of the break opening with negligible aerodynamic atomization,
2. thermal fragmentation due to homogeneous nucleation in the liquid bulk with negligible aerodynamic atomization, and
3. aerodynamic atomization with negligible thermal fragmentation (Appendix C).

A best estimate based on the results of Table I would be a drop size of 16 μm based on homogeneous nucleation, because there is sufficient evidence for this to occur at the LOCA temperature level. Heterogeneous nucleation and aerodynamic forces are also prevalent at LOCA conditions and are therefore additive effects, so the drop size should be less than 16 μm. If drops are formed by some unknown process upstream of the break, the largest drop that can escape fragmentation when passing through the break opening is estimated to be 46 μm according to the assumed conditions and computation in Appendix C.

TABLE I

LOCA-PRODUCED DROP SIZE ESTIMATES

Source Liquid Temperature $\simeq$ 590 K (600°F)

Method of Drop Formation	Further Assumptions	Drop Size, μm
Thermal Fragmentation	Homogeneous Nucleation	16
Thermal Fragmentation	Heterogeneous Nucleation	76
Aerodynamic Atomization	$12 < We_j < 34$	21 to 35
Maximum size that can escape flashing	Break Diameter = 0.3 m (1 ft.)	46

APPENDIX A

EVALUATION OF THE CONSERVATION OF SURFACE ENERGY ASSUMPTION BY ESTIMATING THE DROP SIZES RESULTING FROM A BURSTING BUBBLE

In this appendix, the drop sizes to be expected from the bursting of a vapor bubble are predicted on the basis of conservation of surface energy (and mass). Comparison of the prediction with measurements from Refs. 4 and 5 are then made. The reasonable agreement obtained, considering the problem complexity, provides the confidence needed to justify the Appendix B approximation that surface energy is conserved.

Figure A.1 shows the physical process envisioned. If the bubble film thickness is thin, conservation of mass gives

$$\pi D_b^2 \, \delta \, \rho_\ell \cong \frac{\pi d^3}{6} N \rho_\ell$$

and

$$\frac{\delta}{D_b} = \frac{N}{6} \left(\frac{d}{D_b}\right)^3 , \qquad \text{(A-1)}$$

while conservation of surface energy gives

$$2\pi D_b^2 \sigma = \pi d^2 N \sigma$$

and

$$N = 2 \left(\frac{D_b}{d}\right)^2 . \qquad \text{(A-2)}$$

Combining Eqs. (A-1) and (A-2) to eliminate N results in

$$\frac{\delta}{D_b} = \frac{1}{3} \frac{d}{D_b} . \qquad \text{(A-3)}$$

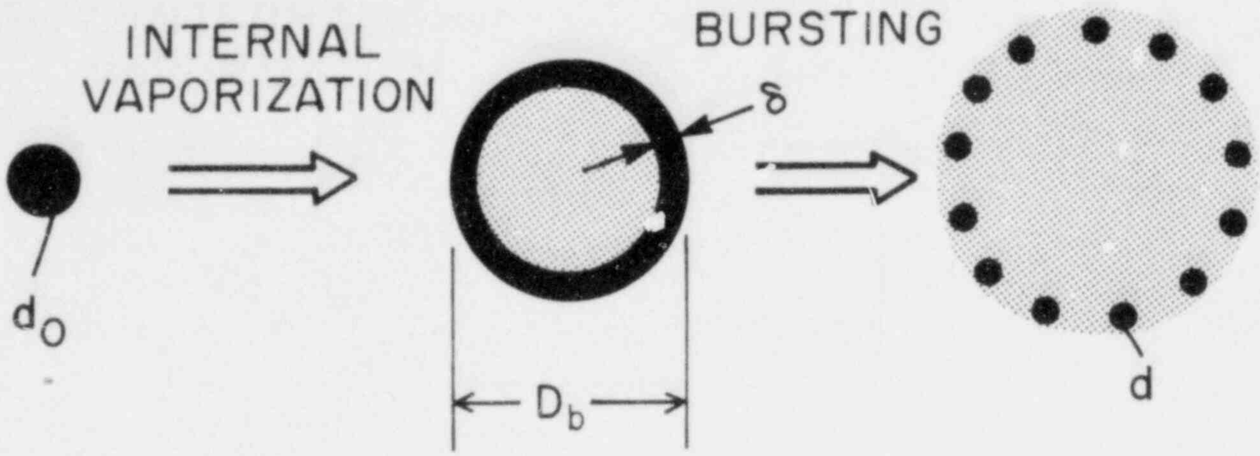

Fig. A.1. Schematic description of (1) an initial preburst liquid sphere of diameter d_0, (2) becoming a bubble due to internal vaporization with diameter D_b and wall thickness δ, and (3) formation of N liquid drops of diameter d after bubble bursting.

To determine values for δ/D_b, the bubble growth-rate constant (originally developed by Forster and Zuber) determined at shattering conditions for a superheated liquid jet in Ref. 1 will be used. The bubble growth-rate constant is

$$C = \left(\frac{C_\ell \, \Delta T}{L}\right)\left(\frac{\rho_\ell}{\rho_v}\right) (\pi \, \alpha_\ell)^{1/2} \; . \qquad \text{(A-4)}$$

Note that the product of the first two parenthetical terms represents the volumetric increases caused by flashing. Using the quality expression

$$X = \frac{C_\ell \, \Delta T}{L}$$

results in

$$C = X(\rho_\ell/\rho_v)(\pi \, \alpha_\ell)^{1/2} \qquad \text{(A-5)}$$

and

$$X \, \rho_\ell/\rho_v = \frac{C}{(\pi \, \alpha_\ell)^{1/2}} \; .$$

Reference 1 shows that C also depends on the nozzle Weber number. Extrapolation to a Weber number equal to zero, which is applicable for the case under consideration, results in a C value of 0.10 $m \cdot s^{-1/2}$. In addition, α_ℓ at room temperature is about 1.4×10^{-7} m^2/s. Thus,

$$X(\rho_\ell/\rho_v) = 149 \ .$$

To determine a δ/D_b, we will use

$$X = \frac{\rho_v \ \pi D_b^3/6}{\rho_v \ \pi D_b^3/6 + \rho_\ell \ \pi D^2 \ \delta} \ ,$$

which upon manipulation gives

$$\frac{\delta}{D_b} = \frac{(1 - X)}{6 \times 149} \ .$$

Substition into Eq. (A-3) results in

$$\frac{d}{D_b} = \frac{(1 - X)}{2 \times 149} \ ,$$

which becomes

$$\frac{d}{D} \simeq \frac{1}{2 \times 149} = 0.0034 \qquad \text{(A-6)}$$

for low qualities. Equation (A-6) is compared with drop-size measurements from Refs. 4 and 5 in Fig. A.2 with reasonable agreement indicated (considering the complexity of the physical process involved).

Of interest is the void fraction (α) at bursting conditions. Defining

$$\alpha \cong \frac{\pi D_b^3/6}{\pi D_b^3/6 + \pi D_b^2 \ \delta} = \frac{1}{1 + 6 \ \delta/D} \ ,$$

using $\delta/D \simeq (1 - X)/(6 \times 149)$ and $X \simeq 0.0$, gives $\alpha \simeq 0.993$.

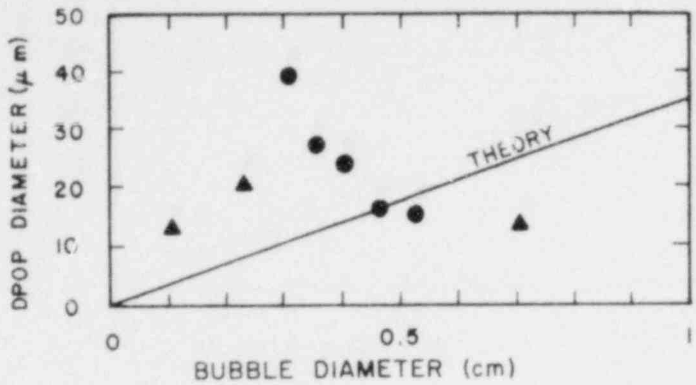

Fig. A.2. Comparison of drop sizes resulting from the bursting of bubbles based on Eq. (A-6) and the experimental data of Refs. 4 (●) and 5 (▲). The Ref. 4 data are presented in Fig. A.3.

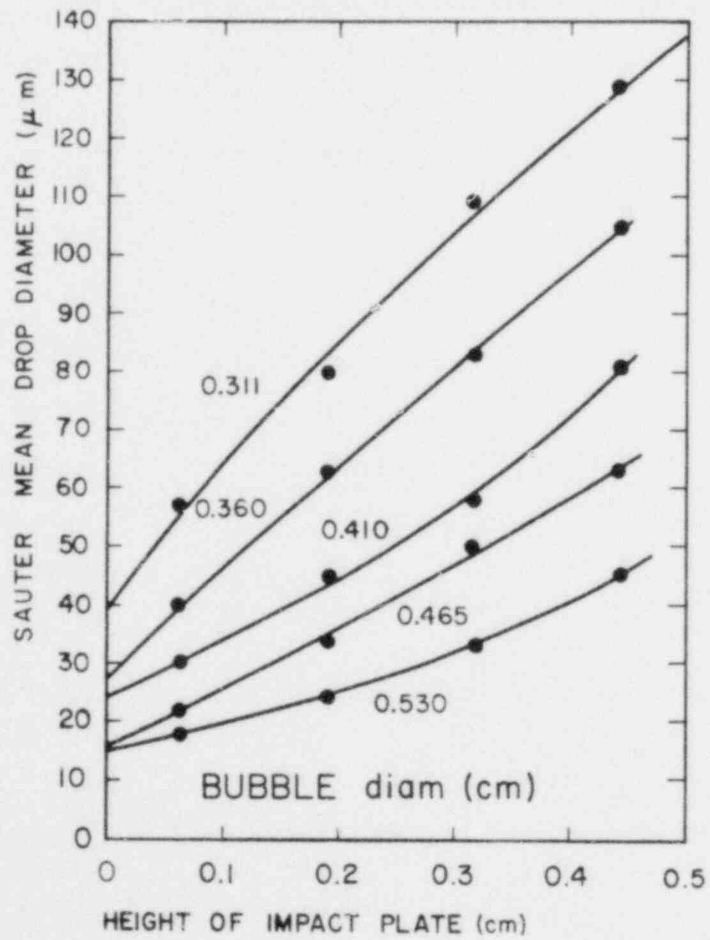

Fig. A.3. Experimental data from Ref. 4 showing the drop sizes measured as a function of the impact plate height above the liquid surface where vapor bubbles of different diameter were generated. Extrapolated values for zero impact height were used in Fig. A.2.

APPENDIX B

THERMAL FRAGMENTATION

If thermal fragmentation is assumed to control and aerodynamic atomization does not have time to act as indicated in one of Fedoseev's tests described in Ref. 3, then we can develop a fragmentation model based on thermodynamics and the phenomenon of free-surface generation as triggered by nucleation. Consider a batch of confined high-temperature liquid at temperature T_ℓ as shown in Fig. B.1. When the constraint is removed, the system will expand and nucleation will occur when the liquid attains a superheated state. Assume the expansion progresses until the bubbles burst and drops are formed, which may occur before the system reaches its final state of mechanical and thermal equilibrium. An analysis for determining drop size follows.

The total number of potential nucleation sites in the system (M_ℓ) is

$$\frac{N\ M_\ell}{\rho_\ell} \ ,$$

where N is the potential heterogeneous and homogeneous nucleation sites per unit volume. Assuming the number of bubbles formed by expansion equals the number of nucleation sites gives

$$X\ M_\ell = \frac{NM_\ell}{\rho_\ell}\ \frac{\pi D^3}{6}\ \rho_v$$

and

$$D = \left(\frac{6}{\pi}\ \frac{\rho_\ell}{\rho_v}\ \frac{X}{N}\right)^{1/3} \ , \qquad \text{(B-1)}$$

where D is the bubble diameter and X is quality. Assuming conservation of surface energy when forming drops

$$\frac{NM_\ell}{\rho_\ell}\ \pi D^2\sigma = \pi d^2\ \sigma\ n \ , \qquad \text{(B-2)}$$

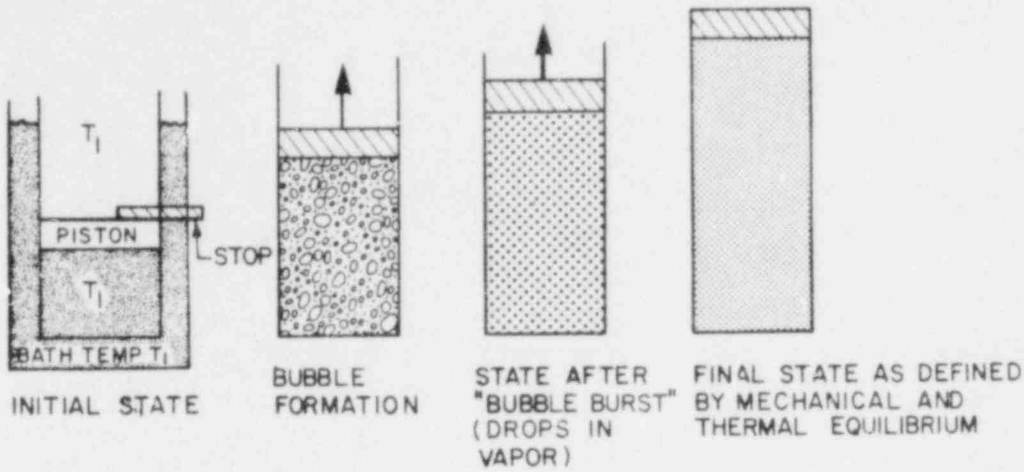

Fig. B.1. Schematic representation of the depressurization of a liquid initially at $T_\ell(T_1)$ resulting in bulk nucleation and bubble formation followed by bubble bursting that generates drops in a vapor and a final equilibrium state.

where σ is surface tension, d is the drop diameter, and n is the number of drops formed. Also, conservation of liquid mass during "bubble burst" results in

$$M_\ell(1 - X) = n\, \rho_\ell\, \frac{\pi d^3}{6} \quad . \tag{B-3}$$

Finally, combination of Eqs. (B-1)-(B-3) results in

$$d = (1 - X)\left(\frac{6}{\pi N}\right)^{1/3}\left(\frac{\rho_v}{\rho_\ell X}\right)^{2/3} \quad . \tag{B-4}$$

To compute the drop size using Eq. (B-4), the thermodynamic state of "bubble burst" must be known as well as the nucleation population density. These can be determined from the experimental evidence found in the literature. Brown and York[1] found that the "bubble growth-rate constant" (originally developed by Forster and Zuber) has a unique value at jet breakup during thermal flashing and that it also depended on the nozzle Weber number. Their results were in the form of two bubble growth-rate constant equations; namely, for $We_j < 12.5$,

$$C = 0.10 - 0.0030\ We_j ,$$

and for $We_j > 12.5$,

$$C = 0.058 - 0.0021\ We_j .$$

The Weber number is given by

$$We = \frac{\rho_g U^2 D_j}{2\sigma} ,$$

where U is the jet velocity and D_j is the jet or nozzle diameter. The bubble growth-rate constant ($m \cdot s^{-1/2}$) is defined as

$$C = \frac{C_\ell\ \Delta T}{L}\ \frac{\rho_\ell}{\rho_v}\ (\pi\ \alpha_\ell)^{1/2} ,$$

where ΔT is the liquid superheat, C_ℓ the liquid specific heat, L the latent heat of vaporization, and α_ℓ is the liquid thermal diffusivity. Note that $C_\ell\ \Delta T/L$ in the above can be replaced by the quality X resulting in

$$C = X \frac{\rho_\ell}{\rho_v} (\pi\ \alpha_\ell)^{1/2} .$$

Bushnell and Gooderum[9] found that the temperature ratio

$$\frac{\Delta T}{T_\ell} = \frac{T_\ell - T}{T} = B ,$$

where ΔT is the superheat and has a unique value at thermal fragmentation for low Weber numbers. Bushnell and Gooderum measured values for B between 0.07 to 0.1.

An expression for drop size d in terms of the experimentally determined parameters C and B can now be developed from the above relationships, namely,

$$d = \left(1 - \frac{C_\ell\ B\ T_\ell}{L}\right)\left(\frac{6}{\pi N}\right)^{1/3} \left[\frac{(\pi\ \alpha_\ell)^{1/2}}{C}\right]^{2/3} . \qquad \text{(B-5)}$$

To develop a rationale for determining the nucleation volumetric density, N in Eq. (B-5), a brief discussion on nucleation follows.

Nucleation can be generated either by wall cavities, impurities, high-energy radiation, other external agents, or by disturbances produced by spontaneous molecular fluctuations. The former is referred to as heterogeneous nucleation and the latter as homogeneous. The activation energy required for heterogeneous nucleation is less than that required for homogeneous nucleation. Near the critical point there is sufficient molecular energy to generate bubbles in the bulk of the liquid. This then represents the breakdown of the metastable thermodynamic state in which heterogeneous nucleation plays the dominant role. Reference 10 presents experimental curves indicating that homogeneous nucleation occurs when

$$\frac{T_c - T}{T_c} \approx 0.11 \quad ,$$

where T_c is the critical temperature (647 K, 705°F). Solving for T results in T = 576 K (577°F), which is in the temperature range where homogeneous nucleation can become dominant.

Reference 13 presents counts of active bubble-producing sites on a heated surface determined throughout the nucleate boiling region. The result was a correlation in terms of the heat flux and the active site population, namely,

$$q = 1345 \sqrt{n} \quad , \qquad \text{(B-6)}$$

where q is in W/m^2 and n is the active sites per m^2. Equation (B-6) is valid in the heterogeneous nucleation regime. By assuming that the bubbles generated by these sites over a length dL are mixed into the channel (diameter D) fluid, we can determine the volumetric population density (N) for use in Eq. (B-5) as follows:

$$\pi D dL \, n = N \frac{\pi D^2}{4} dL$$

$$N = \frac{4n}{D} \quad . \qquad \text{(B-7)}$$

When homogeneous nucleation is achieved near the critical temperature, the volumetric bubble population density increases markedly according to the Gibbs (or Boltzmann's) formula. The corresponding value for N is plotted in Fig. B.2. However, test measurements from Ref. 11 indicate a more modest increase in N with temperature as shown in Fig. B.3. The latter values will be used to estimate the volumetric bubble population during homogeneous nucleation.

To incorporate Eqs. (B-6) and (B-7) into Eq. (B-5), the apparent heat flux at the active sites must be determined. As the pressure drops in the orifice or nozzle, superheat is produced; and if the typical nucleate boiling curve is applicable, the heat flux increases with the superheat until the maximum value is obtained. Reference 14 indicates that the transient boiling curve is approximately the same as that for steady state. The value of the fragmentation superheat temperature ratio (B = 0.07 to 0.1) indicates that the superheat generated at fragmentation is near the point of maximum heat flux, which can then be used in Eq. (B-5) to determine the maximum bubble count density at fragmentation. Figure B.4 presents a plot of maximum heat flux ($\hat{q}$) values vs the boiling temperature for various types of surfaces.[15,16] This plot will be used to determine n using Eq. (B-6) and N using Eq. (B-7). Substituting Eqs. (B-6) and (B-7) into Eq. (B-5) results in

$$d = \left(1 - \frac{C_\ell \; B \; T_\ell}{L}\right)\left(\frac{3}{2} \, D\alpha_\ell\right)^{1/3} \left(\frac{1345}{\hat{q} \, C}\right)^{2/3} \quad , \qquad \text{(B-8)}$$

where $\hat{q}$ denotes the maximum heat flux value as plotted in Fig. B.4 and is evaluated at the fragmentation temperature level, namely,

$$T = (1 - B) \; T_\ell \; .$$

Equation (B-8) is plotted in Fig. B.5 for comparison with test data from various sources that had small orifices and nozzles with 0.25-to 1.2-mm (0.01 to 0.047-in.) diameter. The agreement is reasonable, therefore we will use Eq. (B-8) to predict drop sizes generated by a LOCA assuming heterogeneous nucleation as follows. Let D = 0.3 m (1 ft.), T_ℓ = 590 K (600°F), B = 0.07, and C = 0.1 $m \cdot s^{-1/2}$. The fragmentation temperature T is then

$$T = (1 - 0.07) \times 590 = 549 \, K \; (528°F) \; .$$

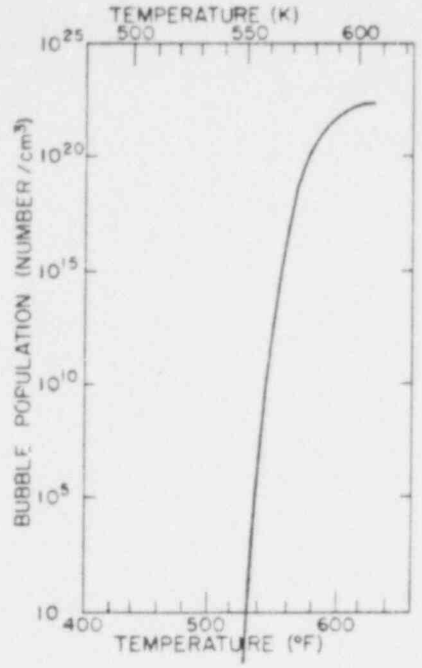

Fig. B.2. Theoretical homogeneous nucleation site population density according to the Gibbs (or Boltzmann's) formula.

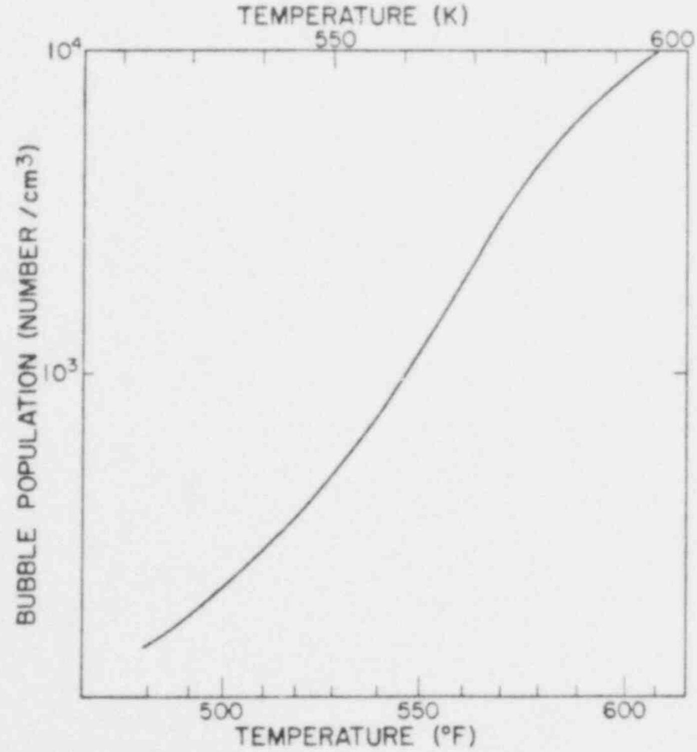

Fig. B.3. Experimental homogeneous nucleation site population density according to Ref. 11.

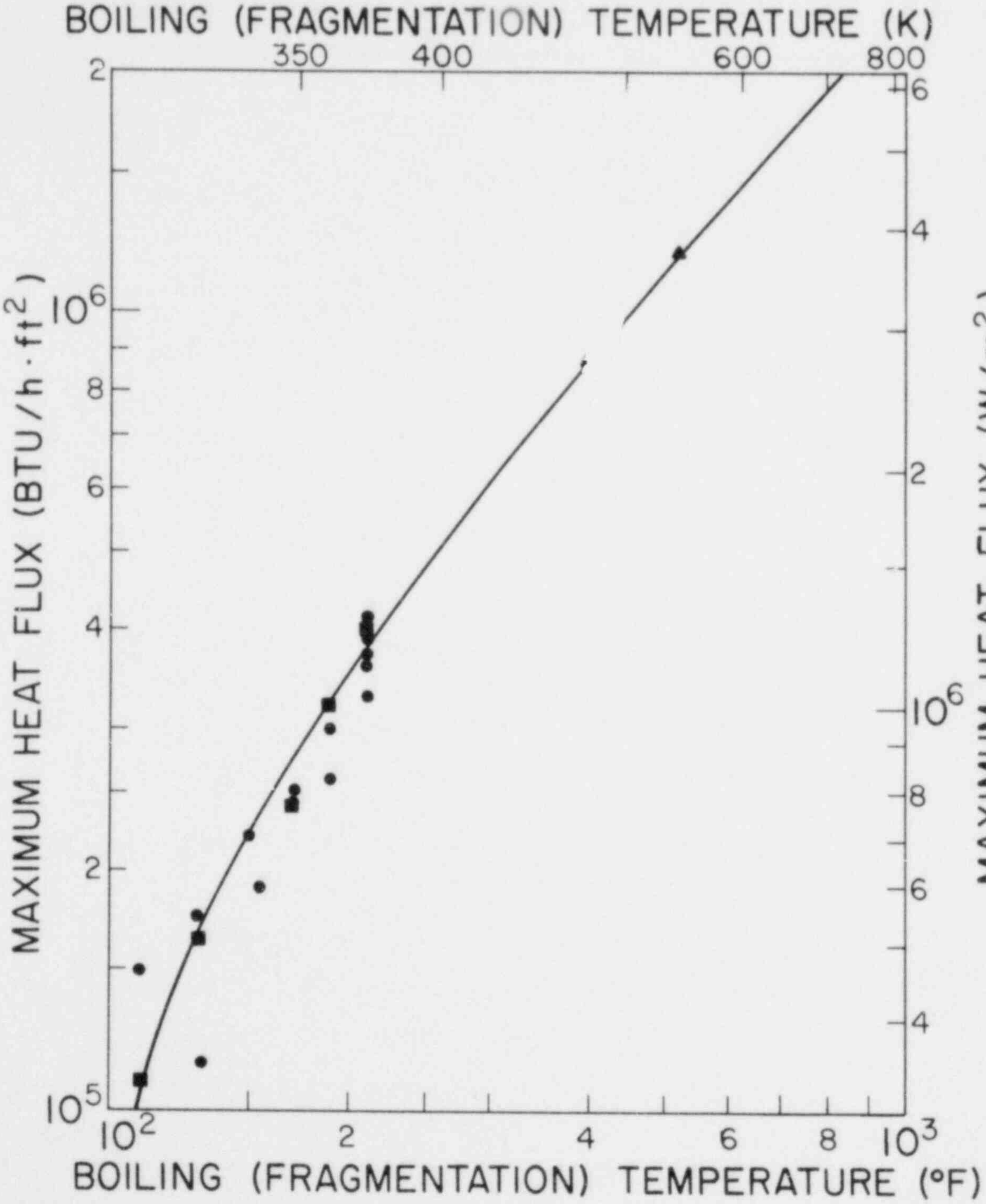

Fig. B.4. Experimentally determined maximum heat flux values (▲ - Ref. 16, ● - Ref. 15 for various types of surfaces, ■ - Ref. 15 for horizontal tube).

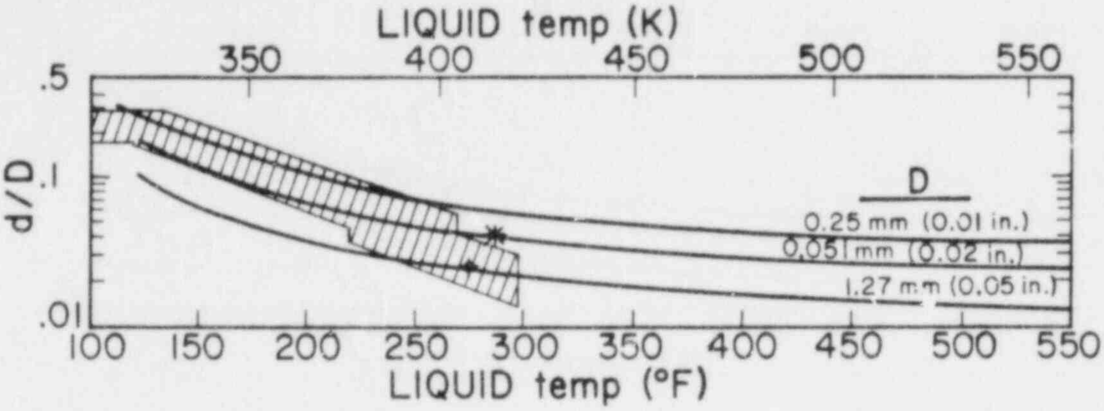

Fig. B.5. Comparison of drop size (d) measurements with predictions (solid lines) from Eq. (B-8) for various orifice and nozzle diameters (D). The cross-hatched area represents many measurements, primarily from Ref. 2, for values of D between 0.25 and 1 mm. The other data are from Ref. 1 (✱ D = 0.8 mm) and Ref. 3 (✦ D = 1.2 mm).

At this temperature, Fig. B.4 indicates a values of $\hat{q} = 3.78 \times 10^6$ W/m^2. Using the water properties at 549 K,

$$\alpha_\ell = 1.17 \times 10^{-7} \text{ m}^2/\text{s} \quad , \quad L = 1.28 \times 10^6 \text{ J/kg} \quad ,$$

and substitution into Eq. (B-8) results in the heterogeneous nucleation drop-size prediction

$$d \simeq 76 \ \mu\text{m} \ .$$

For homogeneous nucleation of water at 590 K (600°F), Fig. B.3 gives a nucleation population of about 10^4 cm^{-3}. Equation (B-6) can now be used to determine an estimated homogeneous nucleation drop size of

$$d \simeq 16 \ \mu\text{m} \ .$$

APPENDIX C

MAXIMUM SIZED DROP THAT CAN ESCAPE FRAGMENTATION

Drop-size estimates based on postulated mechanistic drop formation processes are presented in Appendixes A and B. In this appendix, we will apply an expression from Ref. 7 for the approximate maximum sized drop that can escape fragmentation. As a result, a maximum drop-size estimate is provided that is independent of its formation process.

The Ref. 7 expression for estimating the maximum size (d_m) that can escape fragmentation is based on the drop being exposed to a pressure reduction from P_1 to P_2 in a time interval $\Delta\theta$. In equation form,

$$d_m = 2 \sqrt{\alpha_\ell \frac{\Delta\theta}{G_B}} \ , \qquad \text{(C-1)}$$

where G_B is determined from Fig. C.1 based on the parameter

$$g_B = \frac{0.25}{\ln(P_1/P_2)}$$

and α_ℓ is the drop liquid thermal diffusivity. Although Eq. (C-1) was developed for wet-stream flow in turbines, we will apply it to a LOCA discharge.

To solve Eq. (C-1), we will assume that $\Delta\theta$ can be represented by ℓ/U, where U is a mean velocity over the distance ℓ where the pressure changes from P_1 to P_2. We can then proceed with the estimation by further assuming that

1. ℓ is approximately equal to the break diameter (Ref. 12), which will be assumed to be 0.3 m (1 ft.),
2. U is 146 m/s (480 ft/s) based on Ref. 8,
3. P_1/P_2 is about 2,
4. $G_B = 1/6\ g_B$, which is appropriate, according to Fig. C.1, for the pressure ratio assumed because a value of g_B less than 0.5 results, and

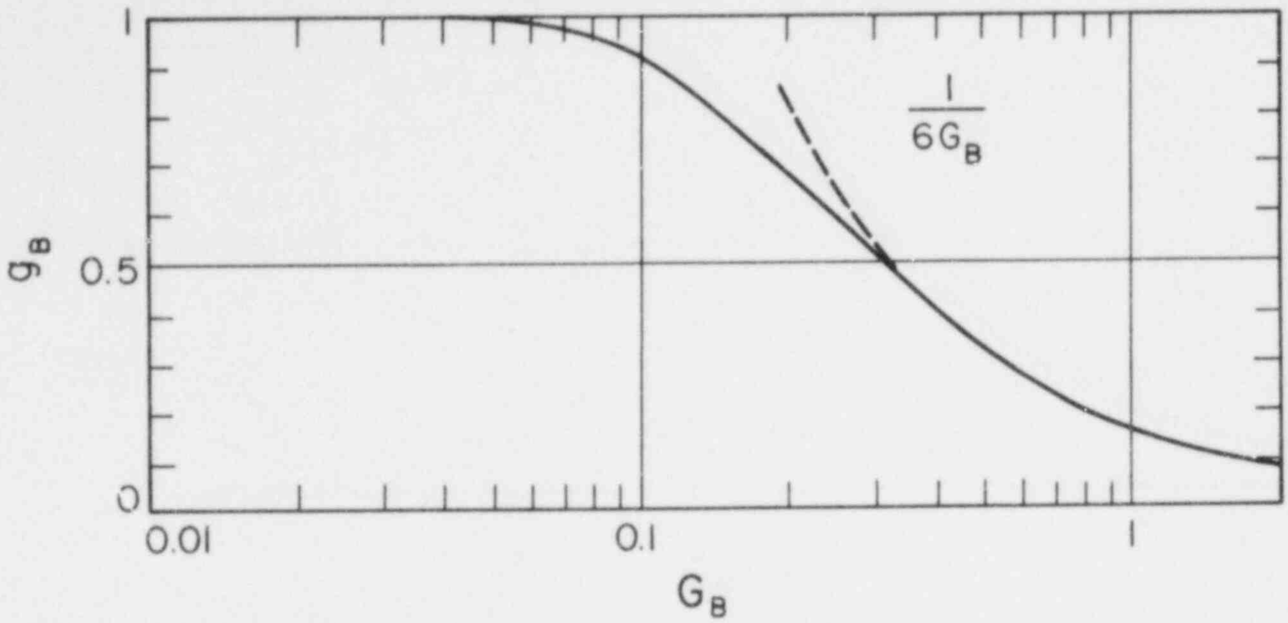

Fig. C.1. Function $g_B(G_B)$ characterizing drop flashing.

5. $\alpha_\ell = 1.2 \times 10^{-7}\ m^2/s$.

An estimated maximum drop size of 46 μm will escape flashing.

Note that flashing will not occur for $g_B \geq 1$ according to Ref. 7 and Fig. C.1. This means that

$$\ln(P_1/P_2) \leq 0.25$$

and

$$P_1/P_2 \leq 1.28\ .$$

For $P_2 = 0.1$ MPa, this requires a $P_1 \leq 0.128$ MPa. The respective saturation temperatures for these pressures are 373 K (212°F) and 381 K (225°F). Thus, the nonflashing condition corresponds to a superheat of about 7 K (13°F), which is near the nonnucleation temperature difference limit for water boiling at atmospheric pressure.

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Drop sizes ranging between 16 and 76 μm are estimated for loss-of-coolant-accident (LOCA) conditions. A break size diameter of 0.3 m (1 ft.) and liquid temperature of 590 K (600 F) are assumed. The best estimate is that the drop size will be less than 16 μm due to the combined effects of heterogeneous and homogeneous nucleation and of aerodynamic atomization. The calculations are based on an extrapolation of available low-temperature fragmentation data to typical LOCA conditions. The extrapolation is supported by a semiempirical fragmentation model that is consistent with low-temperature measurements reported in the literature. If drops are formed by some unknown process upstream of the break, the largest drop that can escape fragmentation when passing through the break opening is estimated to be 46 μm.

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