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Methodology for Calculating Releases from Superheated Flashing Sprays

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Laboratory operations at SRNS involve storing and processing radioactive liquids in various types of containers. These radioactive liquids, when exposed to the high temperatures and heat fluxes during a fire-related event, can become pressurized and heated to temperatures higher than the normal boiling point at atmospheric pressure. The subsequent failure of the container could lead to a situation in which the liquid contents are released as a flashing spray as opposed to a boiling evaporation release.

The purpose of this paper is to:

- Summarize the technical basis for the flashing spray phenomena
- Summarize the information regarding container failure, both analytical and experimental.
- Provide a simple method for calculating ARFs and RFs for various types of containers with different failure mechanism, liquid contents, and thermal challenges.

1 Introduction

Laboratory operations at SRNS involve storing and processing radioactive liquids in various types of containers. These radioactive liquids, when exposed to the high temperatures and heat fluxes during a fire-related event, can become pressurized and heated to temperatures higher than the normal boiling point at atmospheric pressure. The subsequent failure of the container could lead to a situation in which the liquid contents are released as a flashing spray as opposed to a boiling evaporation release.

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- Provide a simple method for calculating ARFs and RFs for various types of containers with different failure mechanism, liquid contents, and thermal challenges.

2 Flashing Phenomena

2.1 Single Component Flashing

If a saturated liquid is of a single-component, a part of the liquid immediately "flashes" into vapor when exposed to a reduced pressure. Both the vapor and the residual liquid are cooled to the saturation temperature of the liquid at the reduced pressure.

If the saturated liquid is a multi-component liquid, the flashed vapor is richer in the more volatile components than is the remaining liquid.

The flash evaporation of a single-component liquid is an isenthalpic (i.e., constant enthalpy) process and is often referred to as an adiabatic (i.e., no heat transfer) flash. The following equation, derived from a simple heat balance, is used to predict how much of a single-component liquid is vaporized.

$$x_f = 100\% \times \frac{(h_u^l - h_d^l)}{(h_d^v - h_d^l)}$$

where:

x_f = weight percent vaporized

h_u^l = upstream¹ liquid enthalpy at upstream temperature and pressure, J/kg

h_d^v = flashed vapor enthalpy at downstream pressure and corresponding saturation temperature, J/kg

h_d^l = residual liquid enthalpy at downstream pressure and corresponding saturation temperature, J/kg

If the enthalpy data required for the above equation is unavailable, then the following equation may be used.

$$x_f = 100\% \times c_p \frac{(T_u - T_d)}{h_{fg,d}}$$

where:

x_f = weight percent vaporized

c_p = liquid specific heat at upstream temperature and pressure, J/(kg °C)

¹ The words "upstream" and "downstream" refer to when the liquid passes from the higher to lower pressure environments.

T_u	=	upstream liquid temperature, °C
T_d	=	liquid saturation temperature corresponding to the downstream pressure, °C
$h_{fg,d}$	=	liquid heat of vaporization at downstream pressure and corresponding saturation temperature, J/kg

2.2 Equilibrium flash of a multi-component liquid [1]

The equilibrium flash of a multi-component liquid may be visualized as a simple distillation process using a single equilibrium stage. It is very different and more complex than the flash evaporation of single-component liquid. For a multi-component liquid, calculating the amounts of flashed vapor and residual liquid in equilibrium with each other at a given temperature and pressure requires a trial-and-error iterative solution. Such a calculation is commonly referred to as an equilibrium flash calculation. It involves solving the Rachford-Rice equation:

$$\sum_i \frac{z_i(K_i - 1)}{1 + \beta(K_i - 1)} = 0$$

where:

- z_i is the mole fraction of component i in the feed liquid (assumed to be known);
- β is the fraction of feed that is vaporized;
- K_i is the equilibrium constant of component i .

In a multicomponent system, the equilibrium ratio, K_i , of a given component is defined as the ratio of the mole fraction of the component in the gas phase, y_i , to the mole fraction of the component in the liquid phase, x_i . Mathematically, the relationship is expressed as

$$K_i = \frac{y_i}{x_i}$$

where

K_i	=	equilibrium ratio of component i
y_i	=	mole fraction of component i in the gas phase
x_i	=	mole fraction of component i in the liquid phase

At pressures below 100 psia, Raoult's and Dalton's laws for ideal solutions provide a simplified means of predicting equilibrium ratios. Raoult's law states that the partial pressure, p_i , of a component in a multicomponent system is the product of its mole fraction in the liquid phase, x_i , and the vapor pressure of the component, p_{vi} :

$$p_i = x_i p_{vi}$$

where

p_i	=	partial pressure of a component i , psia
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p_{vi} = vapor pressure of component i , psia

x_i = mole fraction of component i in the liquid phase

Dalton's law states that the partial pressure of a component is the product of its mole fraction in the gas phase, y_i , and the total pressure of the system, p :

$$p_i = y_i p$$

where

p = total system pressure, psia.

At equilibrium and in accordance with the previously cited laws, the partial pressure exerted by a component in the gas phase must be equal to the partial pressure exerted by the same component in the liquid phase. Therefore, equating the equations describing the two laws yields the following:

$$x_i p_{vi} = y_i p$$

Rearranging the preceding relationship and introducing the concept of the equilibrium ratio gives

$$\frac{y_i}{x_i} = \frac{p_{vi}}{p} = K_i$$

For ideal solutions and regardless of the overall composition of the mixture, the equilibrium ratio is a function of only the system pressure, p , and the temperature, T , since the vapor pressure of a component is only a function of temperature. The equilibrium constants K_i are in general functions of many parameters, though the most important is arguably temperature; they are defined as:

$$y_i = K_i x_i$$

where:

- x_i is the mole fraction of component i in liquid phase;
- y_i is the mole fraction of component i in gas phase.

Once the Rachford-Rice equation has been solved for β , the compositions x_i and y_i can be immediately calculated as:

$$x_i = \frac{z_i}{1 + \beta(K_i - 1)}$$

$$y_i = K_i x_i$$

The Rachford-Rice equation can have multiple solutions for β , at most one of which guarantees that all x_i and y_i will be positive. In particular, if there is only one β for which:

$$\frac{1}{1 - K_{\max}} = \beta_{\min} < \beta < \beta_{\max} = \frac{1}{1 - K_{\min}}$$

then that β is the solution; if there are multiple such β 's, it means that either $K_{\max} < 1$ or $K_{\min} > 1$, indicating respectively that no gas phase can be sustained (and therefore $\beta=0$) or conversely that no liquid phase can exist (and therefore $\beta=1$).

Note that, for a binary system, that is, a two-component system, flash calculations can be performed without resorting to the preceding iterative technique. Some examples of this are nitric acid, sulfuric acid, and hydrochloric acid solutions. Also, flashing may need to be considered at lower temperatures than the water boiling point for these solutions which have lower boiling points at atmospheric conditions when highly concentrated.

Flash calculations can be performed by applying the following steps.

Solve for the composition of the liquid phase, x_i .

For a two-component system, these relations can be simplified:

$$\sum_i x_i = x_1 + x_2 = 1$$

$$\sum_i y_i = y_1 + y_2 = K_1 x_1 + K_2 x_2$$

Solving these expressions for the liquid composition, x_1 and x_2 , gives

$$x_1 = \frac{1 - K_2}{K_1 - K_2}$$

and

$$x_2 = 1 - x_1$$

where

x_1 = mole fraction of the first component in the liquid phase

x_2 = mole fraction of the second component in the liquid phase

K_1 = equilibrium ratio of the first component

K_2 = equilibrium ratio of the first component

Solve for the composition of the gas phase, y_i .

From the definition of the equilibrium ratio, calculate the composition of the liquid as follows:

$$y_1 = x_1 K_1$$

$$y_2 = x_2 K_2 = 1 - y_1.$$

Solve for the number of moles of the vapor phase, n_v , and liquid phase, n_l .

Arrange equations to solve for n_v by using the mole fraction and K-value of one of the two components to give

$$n_v = \frac{z_1 - x_1}{x_1(K_1 - 1)}$$

and

$$n_L = 1 - n_v$$

Exact results will be obtained if selecting the second component; that is

$$n_v = \frac{z_2 - x_2}{x_2(K_2 - 1)}$$

and

$$n_L = 1 - n_v$$

where

z_1 = mole fraction of the first component in the binary system

x_1 = mole fraction of the first component in the liquid phase

z_2 = mole fraction of the second component in the binary system

x_2 = mole fraction of the second component in the liquid phase

K_1 = equilibrium ratio of the first component

K_2 = equilibrium ratio of the second component

The equilibrium ratios can be derived from tables of vapor pressure over solutions available in common chemistry handbooks such as **Perry's Chemical Engineering Handbook**.²

2.3 Aerosol Generation Mechanisms

Liquids heated above the boiling temperature of the liquid/solvent/diluent "flash" upon release; that is, the excess heat above the boiling point of the liquid is expended in the bulk vaporization of the liquid and the remaining liquid is fragmented into fine droplets. This section will describe the aerosol generation mechanisms based upon whether the breach in the container occurs above or below the liquid level. If the failure occurs below the liquid level, a jet will form at the breach and lead to enhanced breakup and droplet formation.

2.3.1 Release above Liquid Surface [3]

Three different ARF and RF values are defined for flashing spray release with vessel failure above the liquid level based on the degree of superheat:

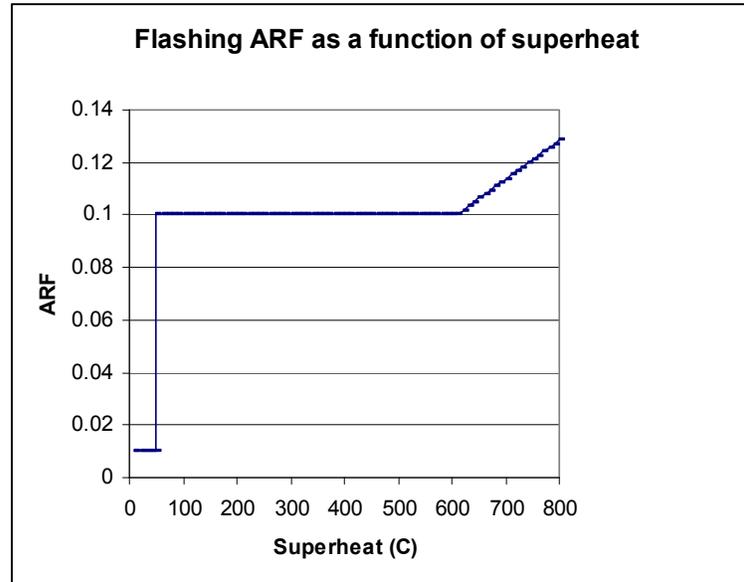
- liquids with less than 50 °C superheat above the boiling point of the liquid;
- liquids with superheats between 50 and 100 °C above the boiling point of the liquid;
and
- liquids with greater than 100 °C superheat.

In order to determine the amount of superheat in the liquid at the time of vessel failure, the material properties of the container must be known. The container materials may degrade significantly at temperatures near boiling at atmospheric pressure. As a result, there may not be any flashing upon vessel failure. Some containers may fail at very high temperatures with a significant flashing release. Due to the wide bound and uncertainties with respect to the level of superheat present in the liquid at the time of vessel failure, ARFs and RF with wide temperature bands have been developed (50°C).

The ARF appears to increase with decreasing source (Material at Risk), size, and volume. The values used in the experiments [4] for these parameters are much less than those anticipated under most accident situation (100 ml), and therefore may be very conservative for certain applications. The ARFs and RFs for flashing spray above the liquid surface are listed in Table 1 below. The effect of the correlation for cases in which the superheat temperature is above 100 °C is displayed in Figure1 for an aqueous solution in which water is the only volatile. The case in which the mass of flashing liquid needs to be calculated is a very high level of superheat (600°C).

Table 1 ARF and RF for Flashing above the Liquid Surface

Superheat	ARF	RF
<50 °C	0.01	0.6
50 to 100 °C	0.1	0.7
>100 °C	Max[0.1, 0.33(MF _g) ^{0.91}] where MF _g is the mole fraction of pressurizing gas/water vapor flashed[5]	0.3

Figure 1 Flashing Release Airborne release Fraction

2.3.2 Break below Liquid Surface [6]

Aerosols also form by a pressurized discharge of subcooled or superheated liquids. Aerosol formation occurs by any of three mechanisms:

1. capillary breakup,
2. aerodynamic breakup, or
3. flashing breakup.

Normally, when a liquid flashes, any contamination such as salt concentrates in the remaining liquid. However, for liquid jets in which flashing leads to jet breakup, the breakup time scale is so short to not allow dissolved solids in the liquid to concentrate and therefore, remain dissolved. As a result, contamination which is dissolved in the flashed liquid will become airborne and will likely all be respirable.

2.3.2.1 Nozzle Effects

Capillary breakup occurs when subcooled liquids are discharged through a very small hole (<2 mm diameter) and form a cylindrical stream which pinches off by surface tension forces to a string of nearly monodisperse drops. The mean droplet diameter resulting from capillary breakup, d_p is proportional to the orifice diameter, D [7]:

$$d_p = 1.9D$$

2.3.2.2 Aerodynamic Entrainment

Aerodynamic breakup occurs with larger punctures with subcooled liquids or slightly superheated liquids. Aerodynamic breakup occurs by mechanical shattering and peeling mechanisms. It is correlated with the Weber number, which is the ratio of shear forces on the

surface of the liquid, proportional to the velocity heads term, $\frac{1}{2} \frac{\rho_g \Delta u_d^2 d_p}{\sigma}$, to surface tension pressure, σ/d_p :

$$We = \frac{1}{2} \frac{\rho_g \Delta u_d^2}{\sigma}$$

Experimentally, droplet breakup occurs at a critical value of the Weber number, We_c , between 12 and 22 [8,9,10]. Rigorously, u_d is the relative velocity of the droplet, that is the drop velocity (equal to the expansion velocity, $u_d = u_{exp}$) minus the wind speed, u_w . Since the wind speed is usually much less than the expansion velocity, only u_d is used. The mean drop size, d_p , is found by rearranging the definition of Weber number, setting $We = We_c$:

$$d_p = \frac{2\sigma We_c}{\rho_g u_d^2}$$

2.3.2.3 Flashing Spray Droplet Generation

Flashing breakup occurs as superheated liquids are discharged and part of the liquid flashes to vapor in the form of bubbles which grow rapidly and break up the surrounding liquid (see examples in Figure 2). An exception is noted by Lienhard and Day [7] who found that jet streams of small diameter cool quickly enough to obviate flashing effects. Larger drops are consequently formed from small-diameter streams.

A correlation for drop size by flashing breakup was developed to fit rainout data from aerosols as a function of superheat¹¹. The correlation is given by

$$d_p = \frac{3 \times 10^4}{10 + 4.0 \Delta T_{sh}}$$

Superheat, ΔT_{sh} , is defined as the excess temperature above the saturation temperature, T_s (the boiling point at the applicable atmospheric pressure):

$$T_{sh} = (T - T_s)$$

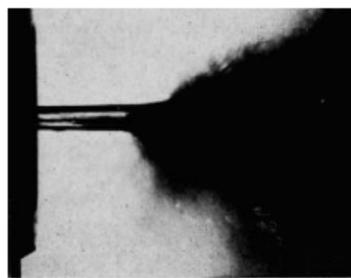


Fig. 3. Flashing jet 10X. Type A, $D = 0.040$ in., $P = 120$ lb./sq. in. $T = 286^\circ\text{F}$.

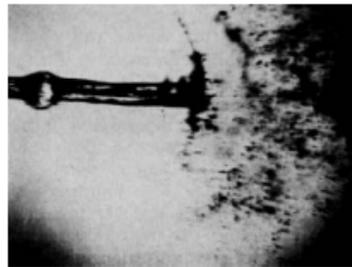


Fig. 4. Flashing jet 10X. Type A, $D = 0.030$ in., $P = 131$ lb./sq. in. $T = 287^\circ\text{F}$. One inch from orifice.

Figure 2 Flashing jet droplet breakup [4]

2.3.2.4 Polydisperse Drop Size Distributions

In order to determine the fraction of the flashing jet spray which is respirable, some information about the aerosol size distribution is necessary. This size distribution can then be

integrated to determine the fraction of aerosols which are respirable. Aerosol drop size distributions are usually found to be log normal. The log normal distribution function $f(t)$ is given in terms of the drop diameter, d_p , and the mean drop size, d_{pm} , by

$$f(t) = \frac{e^{-0.5x^2}}{\sqrt{2\pi} \ln \sigma_G} \quad x = \frac{\ln t}{\ln \sigma_G} \quad t = \frac{d_p}{d_{pm}}$$

Here, σ_G is the standard deviation of the distribution, a smaller number when the distribution is narrow. Typically the log-normal standard deviation ranges $1.3 < \sigma_G < 1.9$. The cumulative distribution is simply the integral of $f(t)$, denoted $F(t)$.

The RF is the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system and is commonly assumed to include particles 10- μm Aerodynamic Equivalent Diameter (AED) and less.

The size of a particle is a function of the measurement technique used. If the method used is optical/electron microscopy or spectrometry, the particle size is a projected diameter measured by the plane that intercepts the light/electron beam or reflection from light scattered by the particle. The size represents the two-dimensional area intercepting the beam and, as with all projections of three dimensions into two, can result in considerable distortion. Projected diameter approximates the Geometric Diameter (D_g).

The Aerodynamic Diameter (DAED) specifically refers to an equivalent sphere with a density of 1 g/cm^3 . DAED is the parameter of interest for defining respirable particles (i.e., $\leq 10\text{-}\mu\text{m}$ AED) as it normalizes materials of differing density. D_g is related to DAED by the equation:

$$D_{AED} = \frac{\left[D_g \sqrt{\rho_p} \left(\left[\frac{C_{c,e}}{C_{c,a}} \right] \right)^{.5}}{\alpha}$$

where:

ρ_p = Particle density (g/cm^3),

$C_{c,e}$ = Cunningham slip factor corresponding to the volume equivalent diameter,

$C_{c,a}$ = Cunningham slip factor corresponding to the aerodynamic equivalent diameter, and

α = Aerodynamic shape factor.

The Cunningham slip factor is related to the potential for particle impact with the mean free path of air molecules. Above the sub-micron size range, all particles impact with air molecules, and the ratio of Cunningham factors can be ignored. The aerodynamic shape factor is not typically known and is assumed to be 1. Therefore, DAED may be estimated from D_g by simply multiplying D_g by the square root of the particle density of density 1 g/cm^3 that exhibits the same terminal velocity as the particle in question.). Since the AED is defined at a density of 1 g/cm^3 , the maximum diameter of interest (Geometric diameter, GD) is [12]:

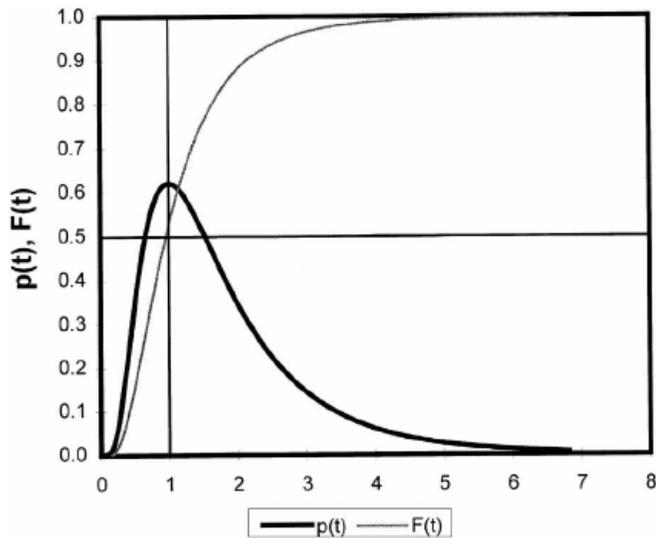
$$D_G = \frac{D_{AED}}{\sqrt{\rho_l}}$$

The RF can then be determined by integrating the particle size distribution

$$RF = \int_0^{D_G} f(r) dr = \int_0^{D_G} \frac{1}{r \sigma_G (2\pi)^{1/2}} e^{\left(-\frac{[\ln(r)-\mu]^2}{2\sigma_G^2} \right)} dr$$

where

$$\mu = d_p \text{ and } \sigma_G = 1.3 \text{ to } 1.9$$



Typical log normal distribution and cumulative distribution of drop sizes for σ_G of 1.9

Figure 3 Log normal distribution and cumulative distribution of drop size

3 Containers and Liquids Susceptible to Flashing Spray Release [13]

3.1 Containers

Failure mechanisms for various types of storage containers used at SRS was evaluated in reference 13 . The container materials included: HDPE, LDPE, PETG, glass, polypropylene, Pyrex, and stainless steel.

3.2 Assessment of Failure Modes

The following discussion is a summarization of Table 2 in Reference 13 which evaluates the failure mode of each container type.

Table 2 Thermophysical properties of container materials

Material	Melting Point (°C)	Heat of Distortion Temperature (°C)*	Vicat Softening Pt [VSP]** (°C) ¹⁴	Thermal conductivity (W/m-)
Thermoplastics				
Polyethylenes				
High Density PE (HDPE)	130	99	125	0.46-0.52
Low Density PE (LDPE)	110	48	95	0.3-0.34
PETerephthalate Glycol (PETG)				
PolyPropylene (PP)	164	99	145	0.12
Teflons				
FEP	270	70	Zero Str. Temperature 225 °C	0.195
PFA	300	NA		0.195
Thermosettings				
Phenolics	NA	200		
Glass Type 1 Borosilicate (Pyrex, etc.)	NA	NA	820°C Strain Pt. 515 °C	1.14

4 Flashing Spray Release Test Program Results [15]

A set of tests to qualitatively assess the failure likelihood and mechanisms for storage containers during a fire was performed by SRNL. A subset of containers was tested to quantitatively determine if a flashing spray release is possible during a fire scenario. The tests

* The **deflection temperature** is a measure of a polymer's resistance to distortion under a given load at elevated temperatures. The deflection temperature is also known as the 'deflection temperature under load' (DTUL), 'heat deflection temperature', or 'heat distortion temperature' (HDT). The two common loads used are 0.46 MPa (66 psi) and 1.8 MPa (264 psi), although tests performed at higher loads such as 5.0 MPa (725 psi) or 8.0 MPa (1160 psi) are occasionally encountered. The common ASTM test is ASTM D 648 while the analogous ISO test is ISO 75. The test using a 1.8 MPa load is performed under ISO 75 Method A while the test using a 0.46 MPa load is performed under ISO 75 Method B.

The deflection temperature test results are a useful measure of relative service temperature for a polymer when used in load-bearing parts. However, the deflection temperature test is a short-term test and should not be used alone for product design. Other factors such as the time of exposure to elevated temperature, the rate of temperature increase, and the part geometry all affect the performance.

** The Vicat softening temperature is the temperature at which a flat-ended needle penetrates the specimen to the depth of 1 mm under a specific load. The temperature reflects the point of softening to be expected when a material is used in an elevated temperature application.

were instrumented to measure the temperature in the beaker surrounding the container and the temperature of the container wall. The tests were also recorded with a video camera.

Heating mantles were connected to a controller with temperature interlocks to prevent over heating. The interlocks were changed depending on the material that was being heated. There were two thermocouples inside the beaker that provided the temperature of the bottle, and these were recorded.

It was determined that two different types of tests would be run on each container type. The first would be a Slow Heat Test. In this test, the digestion bottle was placed in the beaker with the appropriate insert and temperature was increased until the bottle failed. The second test was a Fast Heat Test. In this test, the heating mantle was heated to above the melting point of the particular bottle, but below the temperature where toxic emissions would occur. The bottle was then placed into the insert in the beaker and monitored until failure. The Teflon PFA container had two caps included. The normal cap used in process that has a relief valve in place and a cap with a compression fitting which allowed for additional pressure monitoring inside the container during testing. This second cap did not use the relief valve. Additional tests were conducted using the normal cap where the pressure on the room side of the relief valve was monitored and the alternate cap where the inside bottle pressure was monitored.

The following conclusions flow from the results of the testing:

1. Poly (LDPE, HDPE, PETG and PP) bottles will likely fail at temperatures lower than boiling at atmospheric pressure and above the liquid level. As a result, there will be no flashing spray from the bottles.
2. It is likely that the Teflon PFA digesters will exhibit flashing spray behavior.
3. No failures involving flashing spray release occurred below the liquid level.
4. While the glass vials themselves will withstand very high temperatures, well above the saturation temperature of the fluids, the cap and seal will likely fail at a much lower temperature. The materials (HDPE, PP) used as cap and seals for these containers need to be completely inventoried to determine at what temperature the pressure boundary of the glass vials will fail. This may eliminate all or a major portion of the glass vials from consideration for flashing spray release during a fire event.
5. Failures of the glass vials did not exhibit the kind of violent release (significant liquid ejection) characteristic of high superheat (>50°C) conditions. Therefore, it seems reasonable that if these vials did fail with some superheat that it was likely <50°C and the lower ARF (ARF=0.01) and RF (RF=0.6) could be used for these cases.

5 Suggested Method for Calculating Airborne Release Fraction

This section will outline a methodology for addressing flashing spray on a case-by-case basis.

5.1 Determine if container is susceptible to flashing spray release

The evaluation of material properties, confirmed by the SRNL tests performed on various containers, has identified the following containers as failing before superheat conditions would develop in stored liquids and not susceptible to flashing spray release:

- HDPE
- LDPE
- PETG
- PP

Therefore, these types of containers can be discounted from consideration for a flashing spray release.

This leaves the following type containers for consideration:

- Glass
- FEP Teflon
- TFA Teflon
- Metal

However, these containers may fail before superheat conditions develop based on either the cap or seal material. The following cap or seal materials will fail before superheat conditions develop in the container:

- HDPE
- PP

5.2 Determine container conditions

The contents of the container need to be identified (aqueous solution, HCl, H₂SO₄, HNO₃, etc.) in order to determine what the flashing fraction will be. Also, based on the failure temperature for the container, it may be possible to treat binary solutions as single flashing solutions if the failure temperature is below the boiling temperature for one of the components.

Once the relevant components of the container are known, the thermodynamic properties should be gathered:

- Saturation temperature at atmospheric and failure pressure conditions,
- Specific heat or enthalpy for atmospheric and failure pressure conditions, and
- Heat of vaporization at atmospheric pressure.

5.3 Determine likely failure location for container

Examination of the materials involved in the container (bottle, cap, seal), the minimum failure temperature should be determined. As a result of this evaluation, the location for the release can be determined (above or below liquid level). Also, this evaluation will determine what pressure the liquid will be at for the flashing calculation.

5.4 Calculate flashing fraction

Calculate the flashing fraction based on the single, binary or multi-component methodology outline in Section 2, if necessary.

5.5 Apply appropriate models

5.5.1 Failure of container before flashing conditions develop

Most containers evaluated will fail before the liquid becomes superheated. In these cases, a boiling liquid ARF/RF is the appropriate choice. In the case of fire, it is likely that the temperatures that the liquid will be exposed to after container breach is much higher than the boiling temperature and will lead to vigorous boiling. A bounding ARF for the airborne release from the bubble-burst at the surface for aqueous solutions is 2×10^{-3} with an RF of 1.0. [2]

5.5.2 Failure above liquid level with flashing

For cases in which the failure location is above the liquid level, the ARF and RF values outlined in Table 1 should be used. For superheat conditions greater than 100°C, the flashing fraction from the previous step can be used:

They are repeated herein:

<u>Superheat</u>	<u>ARF</u>	<u>RF</u>
<50 °C	0.01	0.6
50 to 100 °C	0.1	0.7
>100 °C	Max[0.1, $0.33(MF_g)^{0.91}$] where MF_g is the mole fraction of pressurizing gas/water vapor flashed[16]	0.3

After the flashing has occurred, any remaining liquid would then be exposed to fire. Further releases could be possible and the appropriate boiling ARF and RFs should be applied from Reference 3. Note that the remaining liquid has concentrated radionuclides resulting from the flashing evaporation of the liquid component (water, acid).

5.5.3 Failure below liquid level with flashing

For failure below the liquid level while at a superheated conditions, the mechanisms outlined in Section 2.3.2 need to be applied for the aerosol generation mechanism of

- capillary breakup,

- aerodynamic breakup, and
- flashing breakup.

6 Conclusion

The flashing spray release mechanism has been examined with respect to storage and processing containers in use in laboratory facilities at SRNS. The conditions in which flashing spray release could occur in the various containers have been identified. A method for calculating the appropriate ARF and RFs has been outline which considered the container failure mechanism, liquid contents and the specific thermal challenge.

7 References

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- ¹ Ahmed, T, *Equations of State and PVT Analysis: Applications for Improved Reservoir Modeling*, Gulf Publishing Co, Houston TX, 2007
- ² Green, Don W.; Perry, Robert H , *Perry's Chemical Engineers' Handbook* (8th Edition), 2008 McGraw-Hill
- ³ Mishima, J, “*Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*”, DOE-HDBK-3010-94, December 1994
- ⁴ Ballinger, M.Y., S.L. Sutter and W.H. Hodgson, “*New Data for Aerosols Generated by Releases of Pressurized Powders and Solutions in Static Air*”, NUREG/CR-4779, (PNL-6065), Pacific Northwest Laboratory, May 1987, Richland, WA.
- ⁵ Ayer, J.E., A.T. Clark, P. Loysen, M.Y. Ballinger, J. Mishima, P.C. Owczarski, W.S. Gregory, B.D. Nichols.. *Nuclear Fuel Cycle Accident Analysis Handbook*, U.S.N.R.C. - Office of Nuclear Material Safety and Safeguards, May 1988, Washington, DC 20555.
- ⁶ Woodward, J.L., *Estimating the Flammable Mass of a Vapor Cloud: A CCPS Concept Book*, American Institute of Chemical Engineers, New York, NY 1998
- ⁷ Lienhard, J.H., and Day, J.B., “*The Breakup of Superheated Liquid Jets*”, *J. Basic Engineering, Trans AIME*, 515, September 1970.
- ⁸ Brown, R., and York, J.L., “*Sprays Formed by Flashing Liquid Jets*,” *AICHE Journal*, 8, 149–153, 1962
- ⁹ Bushnell, D. M., and Gooderum, P. B., “*Atomization of Superheated Water Jets at Low Ambient Temperatures*,” *J. Spacecraft & Rockets*, 5, 231–232, February 1968.
- ¹⁰ Hinze, J. D., “*Fundamentals of the Hydrodynamic Mechanism Of Splitting In Dispersion Processes*,” *AICHE Journal*, 1 (4), 289–295, 1955.
- ¹¹ CCPS, *RELEASE: A Model with Data to Predict Aerosol Rainout in Accidental Releases*, AIChE, New York, 1998.
- ¹² Carson, D.M. “*Airborne Release Fraction (ARF) and Respirable Fractions (RF) for Food Pack Cans in Fires*”, HNF-9209, Rev. 0, November 2001

¹³ Yeung, R, and Roy, B.N., “*F&H Labs Container Failure Mode Assessment*”, WSMS-SAE-09-0025, 3/4/2009, Washington Safety Management Solutions, Aiken, SC

¹⁴ ***ASTM D1525 - 07 Standard Test Method for Vicat Softening Temperature of Plastics***

¹⁵ Simpson, D, “*Digestion Bottle Demonstration Test Results*”, SRNL-L1400-2009-00100, September 17, 2009

¹⁶ Ayer, J.E., A.T. Clark, P. Loysen, M.Y. Ballinger, J. Mishima, P.C. Owczarski, W.S. Gregory, B.D. Nichols.. *Nuclear Fuel Cycle Accident Analysis Handbook*, U.S.N.R.C. - Office of Nuclear Material Safety and Safeguards, May 1988, Washington, DC 20555.