PNNL-29618, Rev. 0
RPT-SRCRF-001, Rev. 0

Conservative Release Fraction Correlation for Spray Releases

February 2020

PA Gauglitz
RC Daniel

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Washington River Protection Solutions, LLC (WRPS) is planning to conduct repairs in the Liquid Effluent Retention Facility (LERF), and prior to conducting this work they will re-evaluate the hazard category designation for LERF. As part of this evaluation, WRPS needs estimates of the release fraction of potential accidental sprays, because a spray release is a potential bounding accident. The U.S. Department of Energy (DOE) standard for hazard categorization of DOE nuclear facilities (DOE-STD-1027) prescribes the use of bounding estimates for the airborne release fraction (ARF) and respirable fraction (RF) for potential accidents.[1] The ARF is the amount of radioactive material that can be suspended in the air and made available for airborne transport. The RF is the fraction of airborne radionuclide particles (or droplets with or without slurry particles) that can be transported through air and inhaled into the human respiratory system. The RF is commonly assumed to be particles of 10 μm aerodynamic equivalent diameter or less (for water droplets with a density of 1 g/mL, the aerodynamic and physical diameters are equal). The release fraction (R) of respirable droplets from a spray is the product of ARF and RF (R = ARF×RF). In this current study, R is given as a function of droplet diameter and is the cumulative release fraction of droplets less than or equal to droplets of a specified size. R for respirable droplets (ARF×RF) is then determined by evaluating R for droplets ≤ 10 μm.

Pacific Northwest National Laboratory previously developed a conservative correlation for the cumulative generation rate (volume per time) of aerosol droplets less than or equal to specific sizes from spray releases[2] as a function of the spray pressure, orifice area, and droplet diameter. To obtain R estimates from the conservative generation rate correlation, the correlation needs to be recast by dividing the aerosol generation rate by the flow rate of a spray. To support the hazard categorization evaluation of LERF, WRPS has identified four different pipes that could be the source of accidental sprays and has requested release fraction estimates for a spray pressure (87 psig) that is lower than the lowest pressure tested (100 psig) for the spray data used for developing the previous conservative generation rate correlation. Accordingly, there is a need to develop a conservative release fraction correlation that will be evaluated against previous test data and extrapolations and then used to estimate spray releases from specific pipes that are part of LERF.

In the current report, a conservative release fraction correlation, R_C, was developed from the conservative aerosol generation rate correlation developed previously, by dividing the generation rate correlation by the flow rate of a spray using an orifice flow rate equation. Conservative release fraction extrapolations for 87-psig sprays were created by assuming R values for 87-psig sprays were equal to the R values for previously-measured 100-psig sprays. These extrapolations were made for all 100-psig sprays measured previously (47 tests) that had been used in the development of the conservative generation rate correlation. R_C was then compared with previous test data and extrapolations of test data, and the orifice coefficient in the flow rate equation was selected to make R_C conservative. An orifice coefficient of 0.625 matches the average of previous test data for 100-psig sprays, and this orifice coefficient made R_C conservative for all test data and extrapolations of test data. The final conservative release fraction correlation, R_C, uses this orifice coefficient. The R_C correlation is appropriate to use for droplets in the size range of 10 to 100 μm and is reasonably conservative for the range of liquids and slurries tested previously.

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[1] DOE-STD-1027-2018 (Change Notice No. 1). 2019. *Hazard Categorization of DOE Nuclear Facilities*. U.S. Department of Energy, Washington, D.C., and DOE-STD-1027-92 (Change Notice No. 1). 1997. *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports.* U.S. Department of Energy, Washington, D.C.

[2] Daniel RC, PA Gauglitz, CA Burns, MS Fountain, RW Shimskey, JM Billing, JR Bontha, DE Kurath, JJ Jenks, PJ MacFarlan, and LA Mahoney. 2013. *Large-Scale Spray Releases: Additional Aerosol Test Results*. PNNL-22415, WTP-RPT-221, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Four specific LERF pipes were evaluated for the release fraction of respirable droplets (R_C for droplets ≤ 10 μm, which is ARF×RF), assuming a crack size following an established methodology. The largest release fraction for droplets ≤ 10 μm for postulated cracks in these four pipes is $R_C = 2.9 \times 10^{-5}$.

Acknowledgments

The authors would like to thank Phil Schonewill for review of calculations and Lenna Mahoney for both reviewing calculations and her overall review of the report and the resulting improvement in technical clarity. We would also like to thank Bill Dey for his guidance on quality assurance matters and Matt Wilburn for his assistance in editing this report.

Acronyms and Abbreviations

Abbreviations/Acronyms/Definitions

ARF	airborne release fraction
DOE	U.S. Department of Energy
FIO	For Information Only
LERF	Liquid Effluent Retention Facility
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
R&D	research and development
RF	respirable fraction
RTRP	reinforced thermosetting resin pipe
SRCRF	Spray Release Conservative Release Fraction (project)
SOW	Statement of Work
WRPS	Washington River Protection Solutions, LLC
WWFTP	WRPS Waste Form Testing Program

Nomenclature

A	orifice area
C_D	orifice coefficient
d_p	aerosol droplet diameter
GR_C	conservative correlation for aerosol generation rate
Q_S	volumetric flow rate of spray
P_S	spray pressure
R	cumulative release fraction of aerosol droplets
R_C	conservative correlation for release fraction of aerosol droplets
U	average velocity of spray as it exits orifice
ρ_L	liquid density

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1.0 Introduction

Washington River Protection Solutions, LLC (WRPS) is planning to conduct repairs in the Liquid Effluent Retention Facility (LERF), and prior to conducting this work they will re-evaluate the hazard category designation for LERF. As part of this evaluation, WRPS needs estimates of the release fraction of potential accidental sprays,[1] because a spray release is a potential bounding accident. The U.S. Department of Energy (DOE) standard for hazard categorization of DOE nuclear facilities (DOE-STD-1027-2018 2019; and DOE-STD-1027-92 1997) prescribes the use of bounding estimates for the airborne release fraction (ARF) and respirable fraction (RF) for potential accidents. The ARF is the amount of radioactive material that can be suspended in the air and made available for airborne transport. The RF is the fraction of airborne radionuclide particles (or droplets with or without slurry particles) that can be transported through air and inhaled into the human respiratory system. The RF is commonly assumed to be particles of 10 µm aerodynamic equivalent diameter or less (DOE-HDBK-3010-94 2013). For spherical water droplets with a density of 1 g/mL, the aerodynamic and physical diameters are equal (DOE-HDBK-3010-94 2013). The release fraction (R) of respirable droplets from a spray is the product of ARF and RF (R = ARF×RF).[2]

Pacific Northwest National Laboratory (PNNL) previously developed a conservative correlation for the cumulative generation rate (volume per time) of aerosol droplets less than or equal to specific sizes from spray releases (Daniel et al. 2013) as a function of the spray pressure, orifice area, and droplet diameter. To obtain R estimates from the conservative generation rate correlation, the correlation needs to be recast by dividing the aerosol generation rate by the flow rate of a spray. Accordingly, the first purpose of this study is to select a model for estimating the flow rate of a spray and to use this model to develop a conservative release fraction correlation (R_C) based on the existing generation rate correlation.

In addition, the postulated spray releases for evaluating the LERF hazard category designation are at a lower pressure than was used in the development of the conservative generation rate correlation. Accordingly, the second purpose of this study is to evaluate the extrapolation, to lower pressures, of the conservative release fraction correlation, R_C. The evaluation compares R_C to previous spray release data (Daniel et al. 2013) and extrapolations of test data, and adjusts R_C to be reasonably conservative for all conditions.

In the Statement of Work (SOW) for this effort,[1] WRPS requested conservative estimates for the release fraction of respirable droplets (R_C for droplets ≤ 10 µm) for sprays at 87 psig from pipe cracks for the first three specific pipes that are given in Table 1.1. WRPS also requested R_C for respirable droplets from a fourth pipe, which is the last entry in Table 1.1.[3] The SOW further specified that postulated pipe cracks were to be determined using the methodology given in Jivelekas (2016), which states that the critical crack size is one-half the pipe diameter in length and one-half the wall thickness in width. Jivelekas

[1] WRPS requested technical support from PNNL for developing a conservative release fraction correlation and determining the release fraction of respirable droplets from postulated cracks in specific pipes and at a spray pressure of 87 psig. The specific requirements for this work are given in an SOW, Requisition 334060, “Aerosol Release Fraction from PNNL Conservative Spray Release Correlation,” Rev. 0, dated December 2, 2019.

[2] For a spray release, all the liquid in the spray is suspended in the air, so ARF = 1. In this current study, R is given as a function of droplet diameter and is the cumulative release fraction of droplets less than or equal to droplets of a specified size. R for respirable droplets (ARF×RF) is then determined by evaluating R for droplets with diameters of 10 µm or less.

[3] In an e-mail from Susan K. Omberg Carro (WRPS) to Phillip A. Gauglitz (PNNL), on January 7, 2020, with the subject line “FW: LERF Inter-Basin Piping,” WRPS requested that the evaluation of specific sprays include an 8-in. pipe with a 0.140-in. pipe wall thickness.

(2016) selected this methodology to be conservative for spray releases and discussed how this estimate of crack size is corroborated by historical data on piping system breaches. All the pipes listed in Table 1.1 are centrifugally cast, fiberglass-reinforced thermosetting resin pipe (RTRP), ASTM D2997 (2015) Classification RTRP Type II, Grade 1, Class C (see pg A48 of Carson [2012]).[1] The methodology for selecting the critical crack size given in Jivelekas (2016) does not limit the use of the methodology by pipe specification or material of manufacture, though many of the examples of pipe failures used for supporting the method were metallic. In the absence of information on failure modes of RTRP pipes, the method of Jivelekas (2016) was used for determining the critical crack size for the pipes listed in Table 1.1.

Table 1.1. Pipe sizes, wall thicknesses, and spray pressure for selected pipes for LERF.

Pipe Size (inches)	Pipe Wall Thickness (inches)	Spray Pressure (psig)
3	0.100	87
4	0.100	87
4	0.203	87
8	0.140	87

The method for determining the critical breach size given in Jivelekas (2016) was selected to be conservative for spray releases. It provides an estimate for the largest potential breach size, which gives the largest total aerosol generation rate, consistent with aerosol generation rate increasing with orifice size as given in the conservative aerosol generation rate correlation of Daniel et al. (2013). To obtain conservative release fractions for use in evaluating the LERF hazard category designation, a conservative release fraction is needed for the critical crack sizes for the selected pipes given in Table 1.1.

Note that the release fractions of sprays increase with decreasing breach size, but smaller breaches have smaller flow rates and smaller total aerosol generation rates, so smaller breaches do not represent the worst-case, or conservative, spray releases. In order to be conservative for spray releases, the method for determining the critical breach size given in Jivelekas (2016) was selected.

1.1 Previous Spray Release Study

Daniel et al. (2013) discuss previous spray release studies and the development of a conservative correlation (GR_C) for the generation rate of aerosol droplets. Figure 1.1 shows an example of spray release data from that work for the cumulative generation rate as a function of droplet diameter that was typical of the previous testing. Spray release data were collected for different size chambers where the sprays originated at one end of the chamber and travelled the length of the chamber. Figure 1.1 also shows an example of a conservative correlation that is higher than all the test data. Figure 1.2 shows an example of additional test data from the previous work where the measured generation rate is compared with a generation rate correlation, which for this plot was a best fit of the test data and included the effects of droplet diameter, spray pressure, and orifice area. Figure 1.3 compares all the test data and extrapolations of previous test data to 100-ft. chambers against the conservative generation rate correlation that was developed from these test data and extrapolations. In the development of the conservative release fraction correlation, discussed in Section 4.0, spray test data for R will be compared with the conservative release fraction correlation with an equivalent version of Figure 1.3.

[1] In an e-mail from Susan K. Omberg Carro (WRPS) to Phillip A. Gauglitz (PNNL), on February 6, 2020, with the subject line “Re: LERF Inter-Basin Piping Type,” WRPS clarified the specific pipes in Table 1.1 are all fiberglass-reinforced thermosetting resin pipe as given on pg. A48 of Carson (2012).

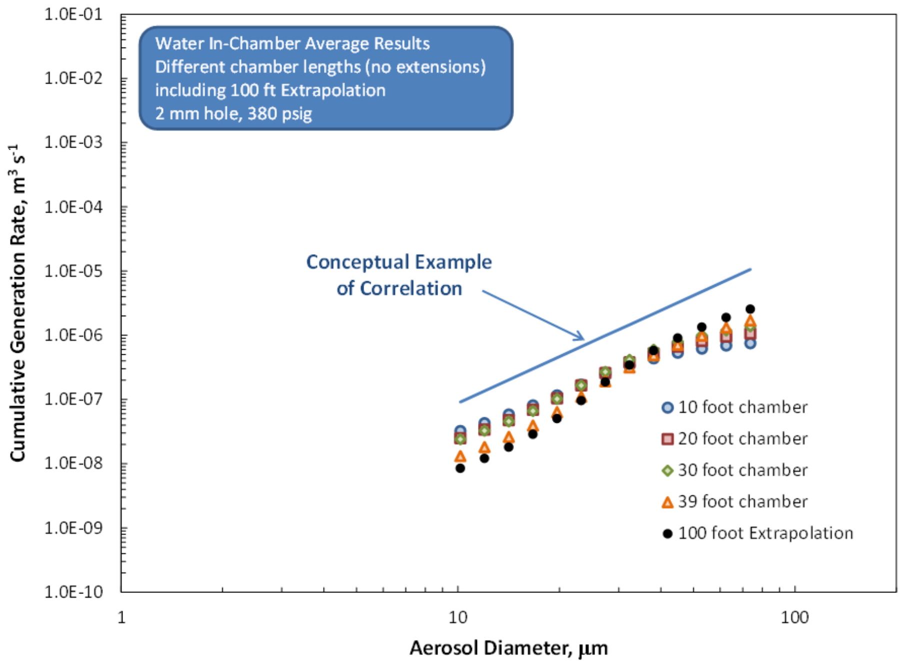

Figure 1.1. Results from the previous study (Figure 10.13 of Daniel et al. 2013) showing examples of test data and an extrapolation to a 100-ft chamber and a conceptual correlation that bounds the highest generation rate of all chamber sizes and the 100-ft chamber extrapolation for a 2-mm hole at 380 psig.

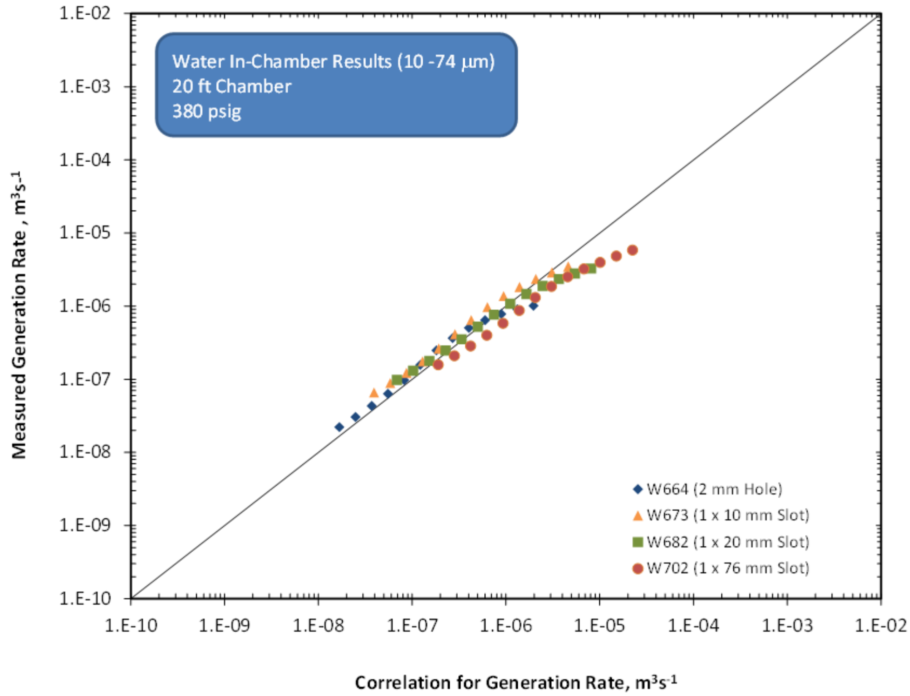

Figure 1.2. Results from the previous study (Figure 10.15 of Daniel et al. 2013) comparing individual test results for measured generation rates with a generation rate correlation given by a best fit correlation of the test data.

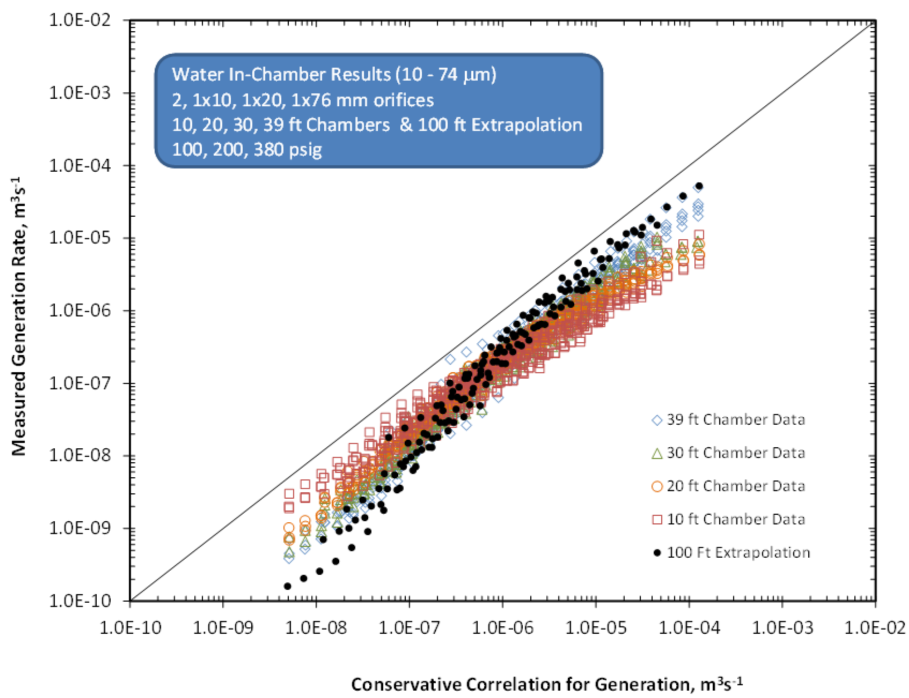

Figure 1.3. Results of previous study (Figure 10.20 of Daniel et al. 2013) showing a comparison of measured generation rates for individual tests and the 100-ft extrapolations with the conservative generation rate correlation GR_C.

2.0 Objectives

The overall objectives of the current study are to (1) develop a conservative correlation for the release fractions (R_C) from accidental sprays based on the previously published correlation (Daniel et al. 2013) for the generation rate of aerosol droplets from sprays and extrapolations of previous 100-psig test data to 87 psig, then (2) use this correlation to estimate R of respirable droplets for the four specific pipes that are part of LERF. The specific objectives of this study are as follows:

- Select a model for estimating the flow rate of a spray and then use this model, together with the existing conservative generation rate correlation (GR_C), to develop a conservative release fraction correlation (R_C). The spray R is the ratio of the aerosol generation rate to the flow rate of a spray.
- Extrapolate previous 100-psig test data, using conservative assumptions, to a spray pressure of 87 psig, which is below the minimum spray pressure of 100 psig used in the previous testing.
- Evaluate the R_C correlation with previous test data, extrapolations of previous test data to 100-ft. chambers, and the new extrapolations to 87-psig sprays and adjust the correlation to be reasonably conservative for all conditions. This correlation can then be used to estimate R of respirable droplets for the four specific pipes that are part of LERF.
- Determine crack sizes and respirable fractions (R_C evaluated for droplets 10 μm or smaller) for four specific pipes sizes, wall thicknesses, and spray pressure needed for evaluating the hazard category of LERF.

3.0 Quality Assurance

This work began with funding from WRPS under Contract 36437-290, *PNNL Support to Chief Technology Office* (Requisition #330813, Rev. 0, dated August 27, 2019, PNNL project 75633), and was completed under Contract 36437-302, *Aerosol Release Fraction from PNNL Conservative Spray Release Correlation* (Requisition #334060, Rev. 0, dated December 2, 2019, PNNL project 75861). This work was conducted as a single effort as the Spray Release Conservative Release Fraction (SRCRF) project and implemented the quality assurance (QA) requirements described below.

All research and development (R&D) work at PNNL is performed in accordance with PNNL's Laboratory-Level Quality Management Program, which is based on a graded application of NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Applications*, to R&D activities. To ensure that all client QA expectations were addressed, the QA controls of the WRPS Waste Form Testing Program (WWFTP) QA program (QA-WWFTP-001), and associated implementing procedures, were also implemented for this work. The WWFTP QA program implements the requirements of NQA-1-2008, *Quality Assurance Requirements for Nuclear Facility Applications*, and NQA-1a-2009, *Addenda to ASME NQA-1-2008*, and consists of the *WWFTP Quality Assurance Plan* (QA-WWFTP-001) and associated QA-NSLW-numbered procedures that provide detailed instructions for implementing NQA-1 requirements for R&D work.

Specific details of the SRCRF project's approach to assuring quality are contained in *Project Quality Assurance Plan: Spray Release Conservative Release Fraction* (SRCRF-QA-001, Rev. 1) and associated implementing procedures. The QA plan describes how the procedures of the WWFTP QA program were used in conducting the work. The work described in this report was assigned the technology level "Applied Research," and was planned, performed, documented, and reported in accordance with procedure QA-NSLW-1102, *Scientific Investigation for Applied Research*. All staff members contributing to the work received proper technical and QA training prior to performing quality-affecting work.

4.0 Conservative Release Fraction Correlation

In this section, a conservative release fraction, R_C, is developed by dividing the conservative generation rate correlation from Daniel et al. (2013) with an orifice flow rate equation. In Section 4.1, a general form of R_C is given with an orifice flow coefficient that needs to be selected to make the correlation conservative. In Section 4.2, orifice coefficients from the previous study (Daniel et al. 2013) measured at spray pressures of 100, 200, and 380 psig are evaluated to support the final selection of the orifice coefficient for use with R_C. Section 4.3 evaluates the R_C correlation with different orifice coefficients in comparison to previous test data and extrapolations of test data, and selects an orifice coefficient that makes R_C conservative for all test data and extrapolations. Finally, Section 4.4 gives the final R_C correlation and estimates of release fraction of respirable droplets for specific pipes for the evaluation of the hazard category of LERF.

4.1 Conservative Release Fraction Correlation

Daniel et al. (2013) give the following results for the conservative correlation for aerosol generation rate from a pressurized spray for the cumulative generation rate of droplets of diameter d_p or smaller:

$$GR_C = 3.26 \text{ x } 10^{-16}\ (A)^{0.793}(P_S)^{2.18}\left(d_p\right)^{2.40} \tag{4.1}$$

where

GR_C = conservative aerosol generation rate (m^3/s)
A = orifice area (mm^2)
P_S = spray pressure (psig)
d_p = droplet diameter (μm)

The cumulative release fraction (R) for of droplets of size d_p or smaller is the aerosol generation rate divided by the flow rate of the spray (Daniel et al. 2013). Using the conservative correlation for aerosol generation rate gives the following for the conservative release fraction, R_C, of a spray:

$$R_C = \frac{GR_C}{Q_S} \tag{4.2}$$

where

R_C = conservative aerosol release fraction
Q_S = volumetric flow rate of the spray (m^3/s)

The flow rate of a spray can be determined from the average velocity and area of the orifice:

$$Q_S = UA/10^6 \tag{4.3}$$

where

U = average velocity of the spray as it exits the orifice (m/s)
A = orifice area (mm^2)

The velocity of the spray leaving an orifice can be determined from the pressure differential, P_S, with an orifice flow equation (e.g., Denn 1980; Daniel et al. 2013):

$$U = C_D \left(\frac{2\,P_S}{\rho_L}\right)^{1/2} \tag{4.4}$$

where

C_D = orifice coefficient (unitless)
ρ_L = liquid density (kg/m^3)
P_S = spray pressure (Pa)[1]

Combining Eqs. (4.1) through (4.4) and assuming a liquid density of 998.2 kg/m^3 for water at 20 °C (CRC 2011)[2] gives the following result for a conservative R correlation with an unspecified orifice coefficient:

$$R_C = 8.77 \text{ x } 10^{-11}\,(A)^{-0.207}(P_S)^{1.68}\left(d_p\right)^{2.40}(C_D)^{-1} \tag{4.5}$$

where the terms in the equations and units are

R_C = conservative aerosol release fraction
A = orifice area (mm^2)
P_S = spray pressure (psig)
d_p = droplet diameter (μm)
C_D = orifice coefficient (unitless)

To finalize the conservative R correlation, R_C, a conservative value for orifice coefficient, C_D, needs to be selected. This will be accomplished by comparing R_C with previous data and extrapolations of previous test data to 87 psig, which is a spray pressure requested for evaluating the hazard category of LERF. In the following section, C_D values from flow rates measured in the previous spray release tests are provided to assist in selecting an appropriate C_D for use in Eq. (4.5).

4.2 Evaluation of Orifice Coefficient

Previous spray release tests described in Daniel et al. (2013) were conducted at spray pressures of 100, 200, and 380 psig. In that previous study, the orifice coefficients C_D for each spray were determined from measured flow rates and pressures, but the summary of the results combined all spray pressures. The orifice coefficients from the previous study have been re-evaluated to determine the average C_D and standard deviation for each of the spray pressures, and Table 4.1 gives the results. The approach for analyzing the data was to first separate orifice coefficients C_D derived from accepted water tests (i.e., all tests listed in Table B.2 of Daniel et al. 2013)[3] by a target test pressure (100, 200, or 380 psig) and then to

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1 In the final equation for R_C, the units for spray pressure will be psig.

2 Using the density for water is appropriate because the conservative generation rate correlation was developed using data from ambient temperature, approximately 20 °C, water sprays.

3 In addition to the tests listed in Table B.2 of Daniel et al. (2013), the current orifice coefficient analysis also includes data from two additional 100 psig water spray tests with the 1×76.2 mm slot (S4A) qualified under previous testing reported by Daniel et al. (2013): tests W379 and W382. The current orifice coefficient analysis also includes test W709, a 200 psig, 1×76.2 mm slot (S4A) that is excluded from the current report's release fraction analysis (Section 4.3). Test W709 is included in Table B.2 of Daniel et al. (2013) but is not included in Table B.5. These three tests (W379, W382, and W709) were included in the previous analysis of orifice coefficients (Figure B.1 and Table B.6 of Daniel et al. 2013) and so they are included in the current analysis (Table 4.1).

determine the average C_D and its standard deviation at each test pressure. For comparison, a global C_D average (and corresponding standard deviation) for accepted water tests was also calculated. The overall average of all the spray tests is C_D = 0.649 and the average for the 100-psig spray tests is C_D = 0.625.

Table 4.1. Orifice coefficient C_D for previous tests for different spray pressures.

Pressure (psig)	C_D		
	Average	Standard Deviation	Data Count
100	0.625	0.101	87
200	0.650	0.073	94
380	0.669	0.067	94
Global	0.649	0.083	275

4.3 Evaluation of Conservative Release Fraction Correlation

Spray test data for aerosol generation rate and spray flow rate from the previous study (Daniel et al. 2013) were used to determine measured *R* values (generation rate divided by flow rate) for each of the tests used in developing the conservative generation rate correlation. A listing of these specific tests is given in Table B.2 of Daniel et al. (2013) and the test conditions are given in Table B.5. Only test data from water sprays where the spray distance (spray orifice distance from splash wall in Table B.2) was 1 ft less than the length of each chamber were used in developing the previous correlation, GR_C, and in this work. This set of test data has 47 tests at 100-psig spray pressure and 50 tests each for the 200- and 380-psig spray pressures, for a total of 147 tests.[1]

Measured *R* values were determined by dividing measured generation rates for all chambers, pressures, orifices, and droplet sizes (from 10 to 74 µm) by the measured flow rates, on a test-by-test basis. For the 100-ft extrapolated *R* values derived from experimental data, the generation rates determined by extrapolating test data to 100-ft chambers by Daniel et al. (2013), for all pressures, orifices, and droplet sizes, were divided by the averages of measured flow rates from the tests (typically about a dozen tests) used in making each extrapolation.

Figure 4.1 shows the measured release fractions for the previous test data and extrapolations to 100-ft chambers in comparison to the R_C with an orifice coefficient of 0.625. The measured values for all test chambers and extrapolations to 100-ft chambers are all less than the R_C with an orifice coefficient of 0.625 and the spread of the measured *R* values is similar to the spread of measured generation rates given in Figure 1.3. The next step is to create extrapolations of test data to 87-psig sprays, which is the spray pressure needed for the hazard category evaluation of LERF.

1 There are three reasons why the total number of tests used in the current orifice coefficient analysis (Table 4.1) differs from the number of tests used in the current release fraction analysis. First, the orifice coefficient analysis included a number of tests from Table B.2 of Daniel et al (2013) that were appropriate for orifice coefficient estimation but had not been included in the development of the conservative generation rate correlations, GR_C, because they had shorter spray distances. Second, one of the Table B.2 tests (W709, 200-psig, 1×76.2 mm slot, 10 ft. chamber) that was included in the current orifice coefficient analysis (Table 4.1) has not been included in the release fraction analysis because this test had been omitted from Table B.5 of Daniel et al (2013). Third, two 100-psig tests (W379 and W382) that were not part of Table B.2, but that had been qualified under the previous testing reported by Daniel et al. (2013), were included in the current orifice coefficient analysis but not in the release fraction analysis. These tests were both at 100-psig, using the 1×76.2 mm slot.

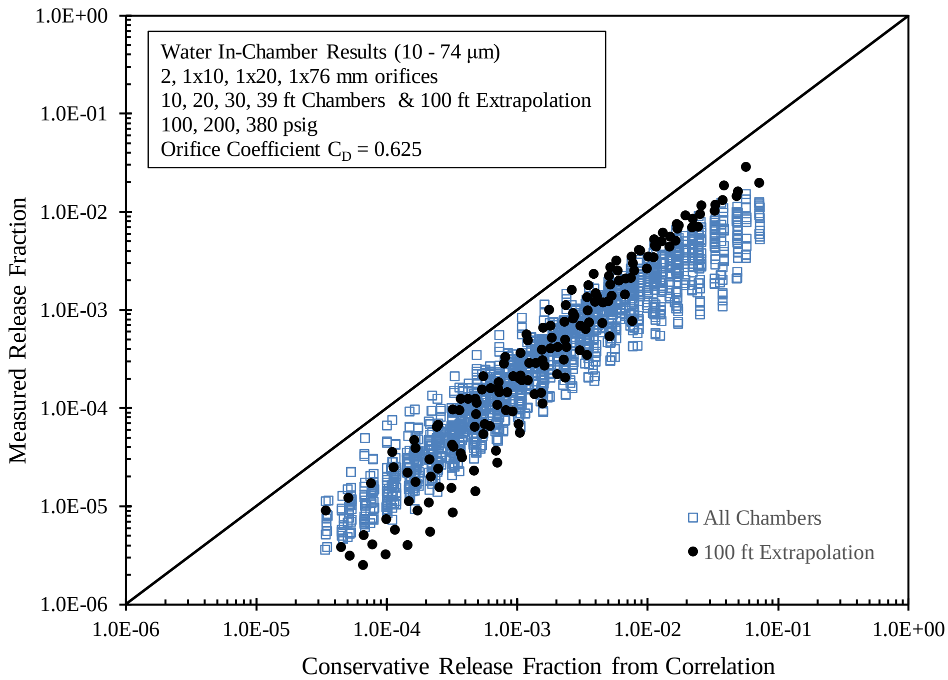

Figure 4.1. Measured release fractions compared to the conservative R_C correlation with an orifice coefficient of C_D = 0.625.

Daniel et al. (2013) evaluated the effect of spray pressure on measured release fractions and showed that the *R* values are always decreased with decreasing spray pressure. A new set of extrapolated 87-psig *R* values was generated by conservatively assuming that for each 100-psig test (including only the 47 actual tests, not 100-ft extrapolations) the *R* at 87 psig was equal to that measured at 100 psig. Figure 4.2 shows an example of an extrapolation of 100-psig test data to 87 psig, together with the 100-psig test data (Test W723 of Daniel et al. 2013), in comparison to the conservative R_C correlation with an orifice coefficient of C_D = 0.625. Each red data point (extrapolation) has the same *R* as the corresponding 100-psig measured value and is shifted to the left on the x-axis because the R_C correlation is evaluated at a lower pressure of 87 psig.

Figure 4.3 shows the measured *R* values for all chamber sizes and the extrapolations to 100-ft chambers together with all the extrapolations of 100-psig data to 87 psig. These results are compared with R_C where the orifice coefficient is 0.625, which is the average orifice coefficient for the 100-psig sprays (see Table 4.1). Figure 4.4 shows a similar comparison of measured results with R_C where the orifice coefficient is 0.649, which is the global orifice coefficient average (see Table 4.1). With an orifice coefficient of C_D = 0.649, two of the measured or extrapolated *R* values (specifically two data points for an 87-psig extrapolation) are slightly higher than the predicted value from R_C, though this is difficult to see in Figure 4.4. With an orifice coefficient of C_D = 0.625 (Figure 4.3), all the measured and extrapolated *R* values are less than the predicted value from R_C. Accordingly, selecting an orifice coefficient of C_D = 0.625 makes R_C conservative for all test data and extrapolations and this orifice coefficient value will be used for the final R_C correlation.

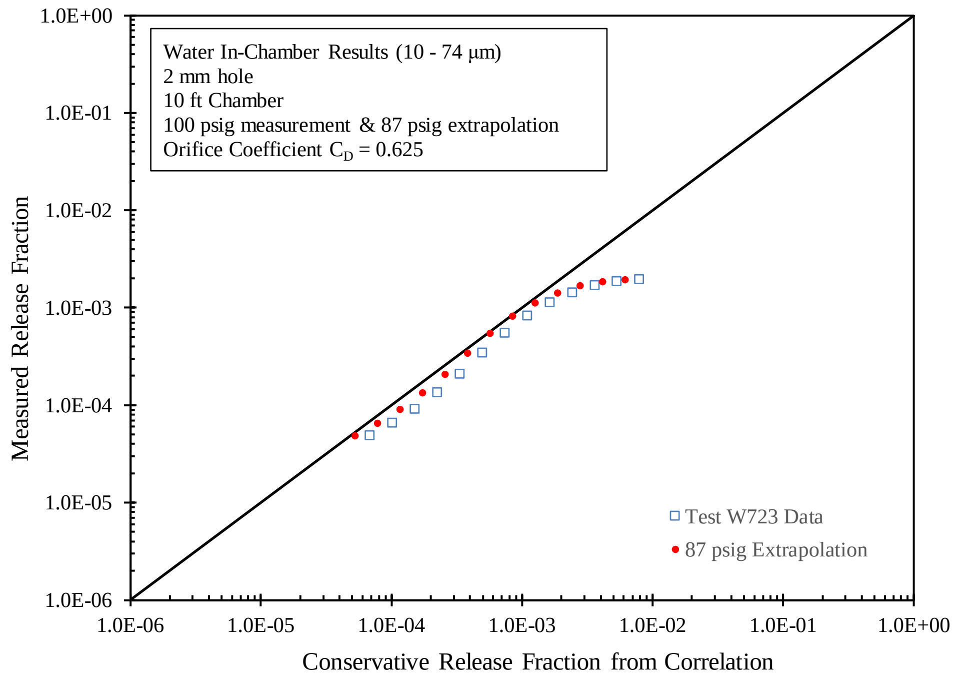

Figure 4.2. Extrapolation of 100-psig test data to 87-psig and 100-psig test data (Test W723 of Daniel et al. 2013) in comparison to the conservative R_C correlation with an orifice coefficient of C_D = 0.625.

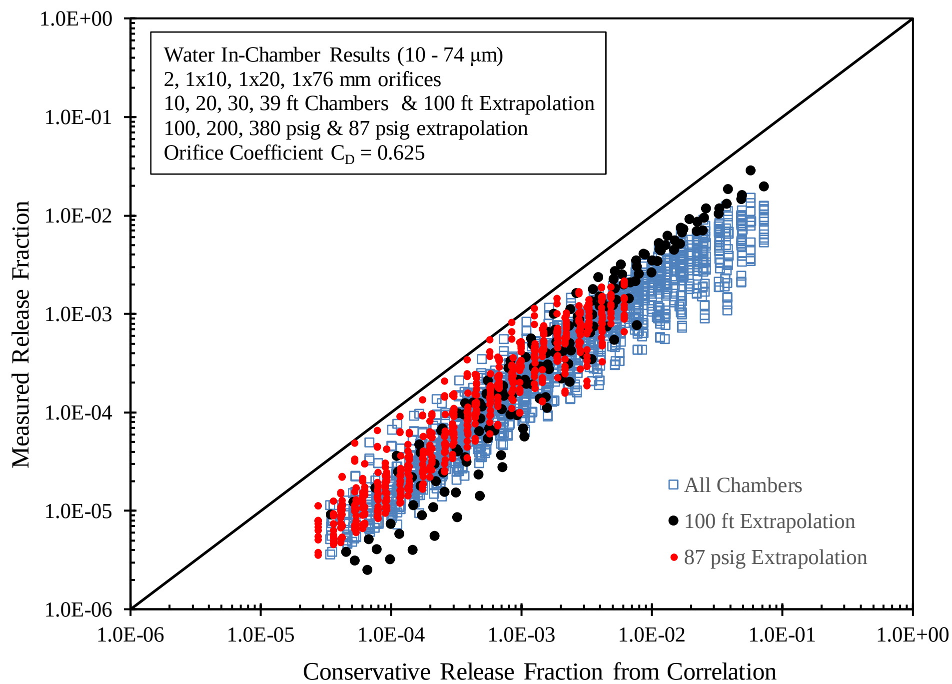

Figure 4.3. Measured release fractions and extrapolations in comparison to the conservative R_C correlation with an orifice coefficient of C_D = 0.625.

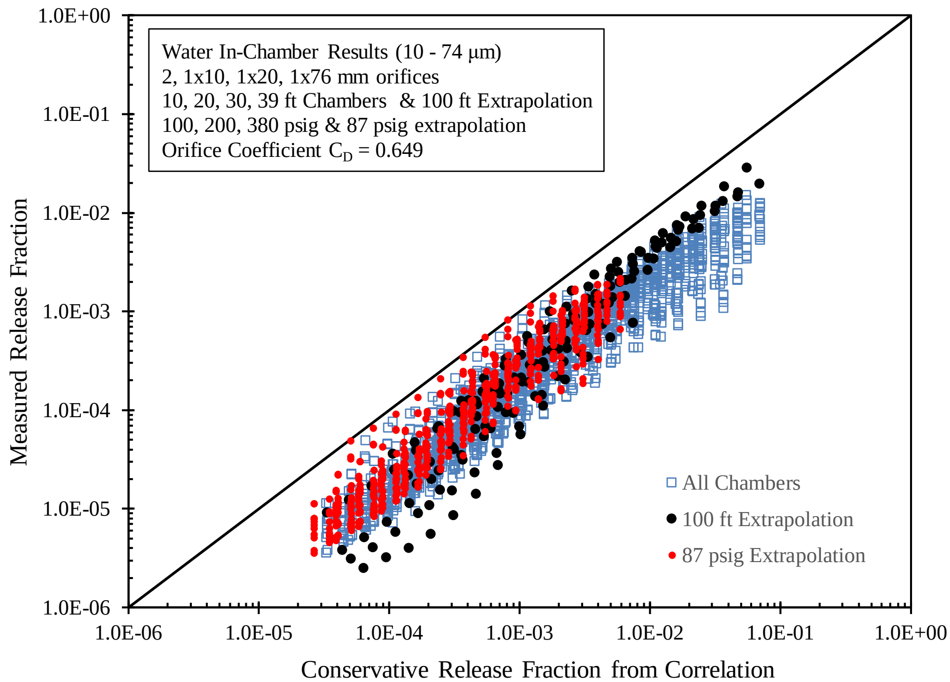

Figure 4.4. Measured release fractions and extrapolations in comparison to the conservative R_C correlation with an orifice coefficient of C_D = 0.649.

4.4 Final Conservative Release Fraction Correlation and Release Fraction Results

In Section 4.3 it was shown that using an orifice coefficient of C_D = 0.625 made R_C conservative for all test data and extrapolations. The final conservative release fraction correlation, R_C, with C_D = 0.625 is given below.

$$R_C = 1.40 \text{ x } 10^{-10}\ (A)^{-0.207}(P_S)^{1.68}(d_p)^{2.40} \tag{4.6}$$

where the terms in the equations and units are

R_C = conservative aerosol release fraction
A = orifice area (mm^2)
P_S = spray pressure (psig)
d_p = droplet diameter (µm)

Figure 4.5 (which is the same as Figure 4.3) compares all test data and extrapolations with the final conservative correlation, R_C. This comparison shows that R_C is conservative for these data and extrapolations.

Daniel et al. (2013) concluded, based on comparing the conservative generation rate correlation with in-spray data, that the conservative generation rate correlation [Eq. (4.1)] was appropriate to use for droplets in the size range of 10 to 100 µm even though the correlation was developed using data for droplets ranging in size from 10 to 74 µm. Accordingly, the conservative release fraction correlation, R_C [Eq. (4.6)], is also appropriate for droplets in the size range of 10 to 100 µm. The conservative generation rate correlation [Eq. (4.1)] used in creating Eq. (4.6) was developed from water spray data, and Daniel et al. (2013) concluded that this correlation was reasonably conservative and appropriate to use for the salt solutions and slurries tested previously, because the aerosol generation rates from the other fluids were overwhelmingly the same or less than water sprays. The one notable exception discussed by Daniel et al. (2013) was that the aerosol generation rates from sprays of non-Newtonian slurries (6- and 30-Pa clays) were not always less than water sprays at the same test conditions, specifically 6-Pa clay slurries for some of the test conditions. However, while the water spray generation rates did not always bound the generation rates from 6-Pa clay sprays, all the test data were less than the conservative generation rate correlation. Figure 4.6 shows a similar comparison of release fraction data for water and 6- and 30-Pa clay slurry sprays in comparison to the conservative release fraction correlations R_C. For these results, the release fractions were determined dividing the measured generation rates with the measured flow rates for the test data in Figure 10.42 of Daniel et al. (2013). The results for the 30-Pa clay are less than, or at most equal to, the water spray results, but the 6-Pa clay release fractions exceed the water spray results in the lower range of release fractions (measured R values on the order of 10^{-5} to 10^{-4}). However, all the release fraction data are less than the conservative release fraction correlation and R_C does adequately bound the measured release fractions for the non-Newtonian (6- and 30-Pa clay) slurries tested previously.

In summary, the conservative release fraction correlation, R_C, is appropriate to use for the liquids and slurries tested previously (see Daniel et al. 2013 for specific liquids and slurries tested) and is appropriate for droplets in the size range of 10 to 100 µm. The conservative release fraction correlation, R_C, can now be used for predicting the release fraction of respirable droplets ($d_p \leq 10$ µm) for specific pipe sizes given in Table 1.1.

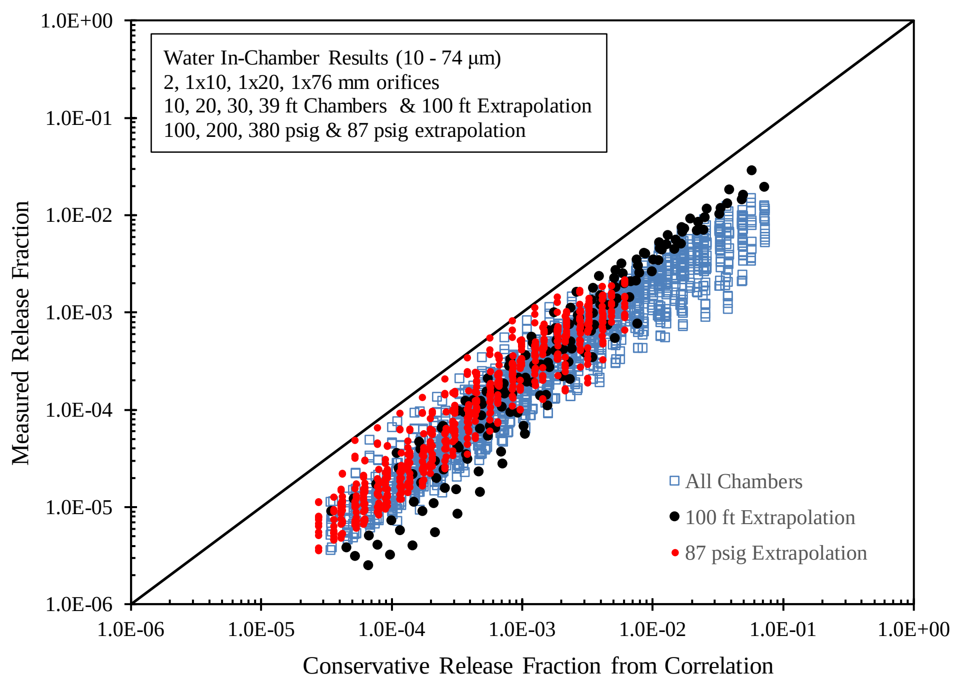

Figure 4.5. Comparison of all measured release fractions and extrapolations of test data to the final conservative R_C correlation.

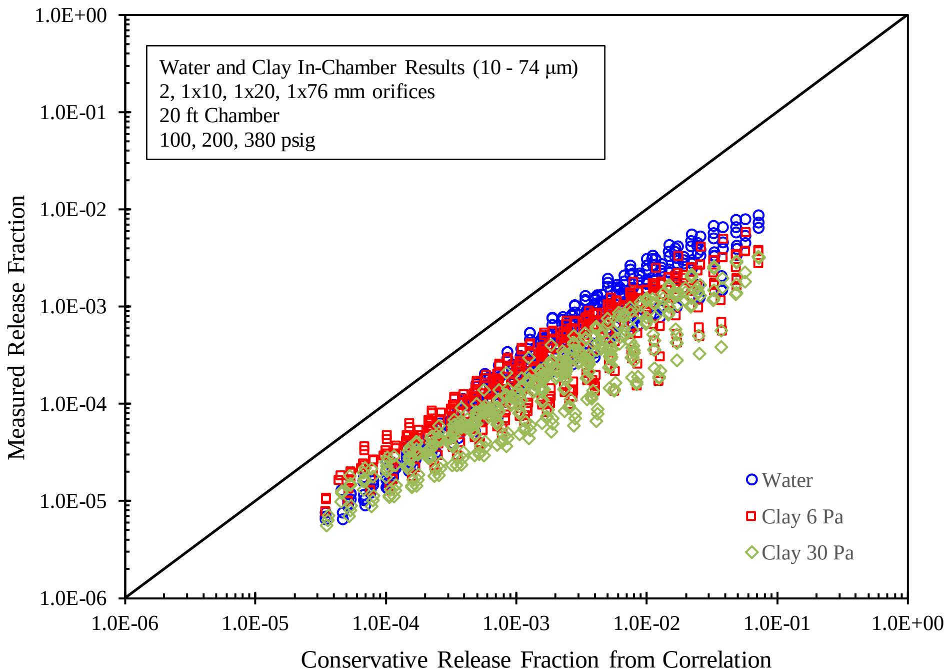

Figure 4.6. Measured release fractions for non-Newtonian slurries (6- and 30-Pa clays) compared with the conservative release fraction correlation R_C.

Table 4.2 gives the postulated pipe cracks, for the pipes given in Table 1.1, using the methodology given in Jivelekas (2016), which states that the critical crack size is one-half the pipe diameter in length and one-half the wall thickness in width. This methodology was selected by Jivelekas (2016) to be conservative for spray releases. Table 4.3 gives the release fraction of respirable droplets ($d_p \leq 10$ µm) for these pipes. The largest release fraction of respirable droplets is 2.9×10^{-5}.

Table 4.2. Pipe sizes, wall thicknesses, and crack sizes.

Pipe Size (inches)	Pipe Wall Thickness (inches)	Crack Length (mm)	Crack Width (mm)	Breach Area (mm^2)
3	0.100	38.1	1.27	48.4
4	0.100	50.8	1.27	64.5
4	0.203	50.8	2.58	131
8	0.140	102	1.78	181

Table 4.3. Pipe sizes, wall thicknesses, spray pressures, breach sizes, and release fractions for droplets ≤ 10 µm from the conservative R_C correlation.

Pipe Size (inches)	Pipe Wall Thickness (inches)	Spray Pressure (psig)	Breach Area (mm^2)	R_C Droplets ≤ 10 µm
3	0.100	87	48.4	2.9×10^{-5}
4	0.100	87	64.5	2.7×10^{-5}
4	0.203	87	131	2.3×10^{-5}
8	0.140	87	181	2.2×10^{-5}

5.0 Conclusions

A conservative release fraction correlation, R_C, has been developed from the conservative aerosol generation rate correlation developed previously by Daniel et al. (2013) using an orifice flow rate equation. The orifice coefficient in the flow rate equation was selected to make R_C conservative.

Release fraction extrapolations for 87-psig sprays were created by assuming *R* values for 87-psig sprays were equal to the *R* values measured for 100-psig sprays in previous testing. Extrapolations were made for all 100-psig sprays measured previously (47 tests) that were used in the development of the conservative generation rate correlation (Daniel et al. 2013). This is a conservative extrapolation.

An orifice coefficient of 0.625 matches the average of previous test data for 100-psig sprays and this orifice coefficient made R_C conservative for all test data and extrapolations of test data. The final conservative release fraction correlation, R_C, uses this orifice coefficient.

The R_C correlation is appropriate to use for droplets in the size range of 10 to 100 μm and is reasonably conservative for the range of liquids and slurries tested previously.

Four specific pipes were evaluated for the release fraction of respirable droplets (R_C for droplets ≤ 10 μm, which is ARF×RF) assuming a crack size following the methodology in Jivelekas (2016). The largest release fraction for droplets ≤ 10 μm for these four pipes and postulated cracks is $R_C = 2.9 \times 10^{-5}$.

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