BETE®
PERFORMANCE THROUGH ENGINEERING

HF Mitigation by Water Sprays

A Summary of Design Considerations by Nozzle Selection

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General Considerations for Mitigation of Accidental Release of Hydrogen Fluoride

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Portions of the following have been abstracted from “On the Road to HF Mitigation” by R.L. Van Zele and R. Diener, Exxon Research and Engineering Co. in Florham Park, N.J. and Effectiveness of Water Spray Mitigation Systems for Accidental Releases of Hydrogen Fluoride, prepared by the Industry Cooperative HF Mitigation/Assessment Program. The article originally was published in the June 1990 issue of Hydrocarbon Processing and was submitted on behalf of the ICHMAP Steering Committee.

THE HAZARDS OF HYDROGEN FLUORIDE (HF) have long been recognized. However, full-scale industry-sponsored HF release tests conducted at the U.S. Department of Energy (DOE) test site in 1986 caused additional concern in view of HF’s toxicity. Ambient impacts were greater than anticipated, and diking, a primary mitigation technique, proved ineffective for releases of pressurized superheated HF.

In partial response to these new technical data, an ad-hoc **Industry Cooperative Hydrogen Fluoride Mitigation Assessment Program** (ICHMAP) was begun in late 1987 to study and test techniques for mitigating accentual releases of HF and alkylation unit acid (AUA). AUA is a mixture of HF and hydrocarbons. It represents most of the total HF inventory of a typical HF alkylation plant.

The ICHMAP has recently released a report (**Effectiveness of Water Spray Mitigation Systems for Accidental Release of Hydrogen Fluoride)** following several year’s study of water spray mitigation systems. BETE has been closely involved in this study component, providing test nozzles and the use of our lab facilities.

The nozzles used in the water spray component study were the BETE **TF 20 FCN** and the **TF 16 FCN.**

Operated at 100 psi, the **TF 16 FCN** will flow at 16.7 GPM and produce a spray with a Sauter Mean Diameter of approximately 210 m. Under the same conditions, the **TF 20 FCN** will flow 26.1 GPM with a Sauter Mean Diameter of 250m.

The BETE TF series spiral nozzle line produces sprays composed of droplets thirty to fifty percent smaller than conventional designs at equivalent pressures. This finely atomized spray presents an extraordinarily large amount of droplet surface area over which mass transfer can occur. The nozzles are a compact, one-piece design having no internal plates or disks.

The absence of internals makes the **TF series** a low-maintenance unit remarkably resistant to clogging. The expanded spiral nozzles, the BETE **TFXP series**, achieve a free-passage diameter equal to the orifice diameter.

These same outstanding performance characteristics of the BETE Spirals have earned them the recognition as the ***nozzle of choice*** for critical cooling and fire suppression appliances. In environments ranging from gas wellhead protection to the safeguarding of ship-borne ammunition magazines, the BETE Spirals are providing unmatched fire control and cooling capabilities.

The assessment

ICHMAP screened numerous potential mitigation techniques for accidental HF releases. Included were techniques such as total enclosures with exhaust scrubbers, liquid containment dikes, form application, water sprays, vapor barriers, and surface tension modifying agents.

Water sprays and vapor barriers were judger the most promising for additional research.

ICHMAP mitigation components consisted of both water spray and vapor barrier programs. The water spray program investigated the effectiveness of water or augmented water application systems in mitigation accidental releases of both HF and AUA. The vapor barrier program assessed the effectiveness of vapor barriers in delaying and diluting accidental releases of heavier-than-air HF vapor clouds in an industrial setting. The program also determined what impact such barriers might have on the consequences of an unconfined vapor cloud explosion.

Major Conclusions:

- Water, applied via either fixed sprays or fire monitors, is effective in removing HF, HF removals of 25% to 90+% were demonstrated at water-to-HF liquid volume ratios of 6/1/ to 40+/1.
- Vapor fences can reduce near-field concentrations, but will have little effect on far-field concentrations and will have little effect on cloud arrival and departure times.
- Vapor boxes (four-sided enclosures with an open top) can reduce both near and far-field concentrations. Far-field concentration reductions are the result of a reduction in the rate of gas being advected downwind. However, such vapor boxes will appreciably increase the consequences of an unconfined vapor cloud explosion in the event of a flammable gas release.
- Large plant obstacles reduce downwind concentration.
- Concentration reductions resulting from large plant obstacles or vapor fences/boxes are very site-specific.

Background

Sound practices for handling HF are in place. The hazards have long been recognized in operating practices have been aimed at minimizing the possibility of a release and mitigating the effects if one should occur.

Prior to 1986, accidental releases of pressurized, superheated HF were commonly thought to form liquid pools. This led to the concept that liquid containment dikes could mitigate the ambient impacts of accidental HF releases.

In the summer of 1986, a series of atmospheric HF release tests were conducted at the DOE test site in Mercury, Nevada (codenamed the GOLDFISH series). These tests concluded that a release of pressurized, superheated HF ***did not*** pool, negating the benefit of liquid containment dikes. Further, the resultant ambient impacts were greater than anticipated because the vapor clouds advected downwind consisted of flashed HF vapor and entrained HF liquid as a finely disperses aerosol. In addition, the GOLDFISH tests demonstrated that water sprays were at least partially effective in mitigating such releases of HF.

ICHMAP was formally established in December 1987 to develop information to better design and implement effective mitigation techniques for accidental releases of HF, and a computer tool to better estimate ambient impacts from accidental HF releases. ICHMAP involved 20 companies, both HF producers and consumers (Allied-Signal, Amoco, Ashland, BP, Chevron, Conoco/DuPont, Dow, Elf Aquitaine, Exxon, Kerr-McGee, Marathon, Mobil, Phillips, Saras, Shell International, Sun/Suncor, Tenneco, Texaco, Unocal, and 3M).

Program components and their major objectives were:

- **Water Spray.** Investigate the effectiveness of water or augmented water application systems in mitigating accidental releases of both HF and AUA.
- **Vapor barrier.** Assesses the effectiveness of vapor barriers in delaying and diluting accidental releases of heavier-than-air HF vapor clouds in an industrial setting and determine what impact such barriers might have on the consequences of an unconfined vapor cloud explosion.
- **Impact Assessment.** Develop validated ambient impact assessment computer models for calculating release rates and jet and plume dispersion of accidental releases of HF.

Water Spray Component

The objective was to investigate the effectiveness of water or augmented water application (via either sprays or monitors) in mitigating accidental releases of both HF and AUA as a function of flow conditions, HF acid and water spray properties, and geometric factors. Augmented water refers to water plus additives such as sodium bicarbonate, caustic, or surfactant. This work was in large part a follow-up to the 1986 GOLDFISH series. GOLDFISH included three water spray tests that demonstrated 35% to 55% HF removal efficiency. These tests provided valuable information, but they were limited in scope and detail. Several key questions went unanswered.

A series of bench-scale laboratory and larger-scale field tests were conducted in controlled humidity/wind speed flow chambers. The bench-scale experiments identified key variables for testing in larger-scale field tests. In the larger-scale field tests, HF and AUA removal efficiencies were measured as a function of variables such as water-to-HF liquid ratio, water application method (sprays, fire monitors), water additives (neutralizing agents, surfactants), distance of the water application to the release point, water application droplet size, ambient relative humidity, etc.

It was outside the scope of this work to generate generic design criteria for water mitigation systems, since each application depends on many local factors. However, conclusions can guide those responsible for designing mitigation systems. To this end, two separate computer models were developed to assist in assessing the effect of various water application design parameters on HF removal efficiency.

Overview, lab test program

The objective of the small-scale laboratory test program was to help define the test matrix for the larger scale field-testing, to evaluate design criteria for a larger flow chamber, and to gain operating experience with HF and AUA for the larger unit.

Among key variables identified, the water flow rate at a constant acid flow rate was clearly the dominant variable. In addition, HF removal efficiency increases as droplet size of the water spray decreased. Among various water additives tested, which included $NaHCO_3$, $CaCl_2$, NaOH, and surfactant, only NaOH shower a marginal increase in removal efficiency compared to pure water.

Overview, field test program

A series of 87 large-scale field tests was conducted in which the effect of major variables on the HF removal efficiency of water or augmented water, applied via either sprays of a fire monitor, was determined. This test series also included seven tests in which aerosol particle sizes were measured.

The 87 tests were conducted at DOE's liquefied gaseous fuels spill test facility, near the Mercury, Nev. test site. They were termed the HAWK series.

Pressurized, superheated HF, either in pure anhydrous form or in the form of AUA, was released at controlled pressure and temperature into a totally enclosed flow chamber (14-0 feet long, 16 feet high, 8 feet wide) and contacted with water or augmented water.

In the chamber, water was applied via either sprays or a fire monitor. The HF was released from a square-edged orifice at a normal rate of approximately 6 gpm. Steam and water spray grids at the chamber inlet allowed for control of both air humidity and temperature. In addition to releases of pressurized HF, several tests were conducted to assess the HF removal efficiency of water sprays for HF pool evaporation releases.

Impact of variables

The impact of the following variables on HF removal efficiency was determined:

- Water liquid volume ratio
- Water spray application geometry:
- Number of sprays per header
- Spray header distance from the release point
- Spray orientation (up flow and down flow)
- Spray header elevation above the release point
- Dual spray headers in series
- Water spray droplet size
- Water application via a fire monitor:
- Application pattern (fog or jet)
- Monitor distance from the release point
- Acid type (anhydrous HF or AUA)
- Acid temperature, pressure
- Water additives (NaHCO3, surfactant, NaOH)
- Ambient relative humidity and wind speed
- Steam as an acid jet dispersant

In addition to measuring HF removal efficiency, seven tests were conducted in which the size of the HF aerosol particles (Liquid HF entrained with the flashed vapor was measured using a particle counter sizer velocimeter (PCSV). The PCSV is a laser-based light scattering instrument which makes direct in-line particle size measurements.

Aerosol droplet measurements

In addition to the water application mitigation tests, a series of tests was conducted in the large-scale flow chamber to measure the size of the aerosol droplets produced when pressurized, superheated HF or AUA is released into the atmosphere.

To briefly summarize the results, the PCSV-P measured predominantly submicron liquid aerosol droplets at the exit of the sharp-edged discharge orifice. The aerosol droplets subsequently grew to larger particles at the outlet of the flow chamber. The presence of submicron particles at the orifice exit point to formation of aerosol by the process of flash atomization breakup as opposed to conventional shear spray breakup. Temperature, humidity, release pressure, radial position in the plume, and type of acid did not appear to have any significant effect on the measured size distributions for the range of conditions investigated. The increase in droplet size at the exit of the chamber is likely due to the condensation of ambient moisture resulting from contact with the cold HF plume.

Damage tests with monitors

Applying mitigation water by fire monitors raises the concern of damage to the unit resulting from rapid activation and application of high pressure, large-volume water monitors. To help assess how serious this concern might be, a series of tests was conducted in which water was applied via fire monitors at rates of 2,000, 4,000, and 6,000 gpm at distances of 7, 15, and 25 feet from the process unit.

The target area included pressure gauges, small-bore piping, control valve stations, and conduit. Water was applied via both a wide-angle fog pattern and a straight jet pattern. The water delivery pressure was approximately 100 psig.

In the most severe test, water was applied in a narrow jet pattern at a rate of 6,000 gpm at a distance of 7 feet from the target area. The resulting damage to the target area was minimal. It consisted mainly of broken pressure gauge glasses, dented insulation, and some loosening of conduit from its supports. The overall integrity of the target area was not affected, i.e., there was no broken piping of instrument tubing.

Summary of Conclusions

Major conclusions from the large-scale field tests are:

- Water-to HF liquid volume ratio was identified as the major variable affecting removal efficiency.
- HF removal of 25% to 90%+ were demonstrated at water-to-HF liquid volume ratios of 6/1 to 40+/1. For comparisons of HF removal efficiency versus water-to-HF liquid volume ratio, a base case was defined with down flow sprays at 8 feet elevation located 16 feet from release point, 320 micron Sauter mean water spray droplet diameter, anhydrous HF.
- Water additives (neutralizing agents, surfactants, etc.) and steam as a jet dispersant had little measurable effect on removal efficiency.

- Water spray removal efficiency increased with:
  - Decreased water spray droplet size nozzles
  - Increasing distance between the spray nozzles (2 feet or 3 feet nozzle spacing versus 1 foot in the base case)
  - Decreasing spray header elevation above the release point (16 feet versus 8 feet in the base case)
- Dual water sprays (i.e., two spray headers in series, separated by approximately 15 feet) had little measurable effect on HF removal efficiency at a constant total water-to-HF liquid volume ratio.
- HF storage pressure appeared to affect HF removals, but adequate data were not collected to isolate the potential effect of other variables.
- Applications where the acid release elevation was at the same level as the spray headers causes severe bypassing of the acid cloud over the header. This resulted in expectedly substantial reductions in removal efficiencies.
- A trend was measured of increasing efficiency with acid pressure. A number of unmeasured variables related to liquid dropout render these tests inconclusive.
- Up flow water sprays provided slightly higher removals than did down flow water sprays. These gains may not be additive to the gains from droplet size reduction.
- There was essentially no difference in HF removal efficiencies between HF and AUA for a constant water-to-total contained HF acid liquid volume ratio.
- Wind speed and relative humidity had little measurable effect on removal efficiency under the conditions tested (50%-90% R.H.; 3.0 to 6.0 meters per second).
- A fire monitor provided better HF removals when operated with a coarse droplet jet pattern aimed directly at the release point from a short distance (as opposed to a wide fog pattern or a jet applied from a greater distance).
- Aerosol produced at the exit of the release orifice was predominantly sub-micron in size. The aerosol particle size was unaffected by acid pressure, acid type, acid temperature, or relative humidity.

Application of test results

In applying the results of this work to conditions different from those in the field tests, due account must be taken of the dynamic interaction between the water spray and the HD cloud. Work has recently been completed by ICHMAP's Water Spray Subcommittee to characterize these interactions. Two separate computer models have been developed to assess the effect of various design parameters such as water-to-HF liquid volume ratio, distance of the water application from the release point, water application method (i.e., up flow or down flow of sprays, fire monitors, etc), on overall HF removal efficiency.

The Base Case

Down flow, single curtain
No additives
Saunter Mean Droplet Diameter of 320 microns
Spray 16 feet downstream of acid orifice
Acid orifice elevation at 3 feet
Spray header elevation at 8 feet
Eight (8) spray nozzles
No steam dispersion of acid
Acid pressure of 60 psig
Acid temperature of 100ºF
Air velocity of 3.0 meters per second

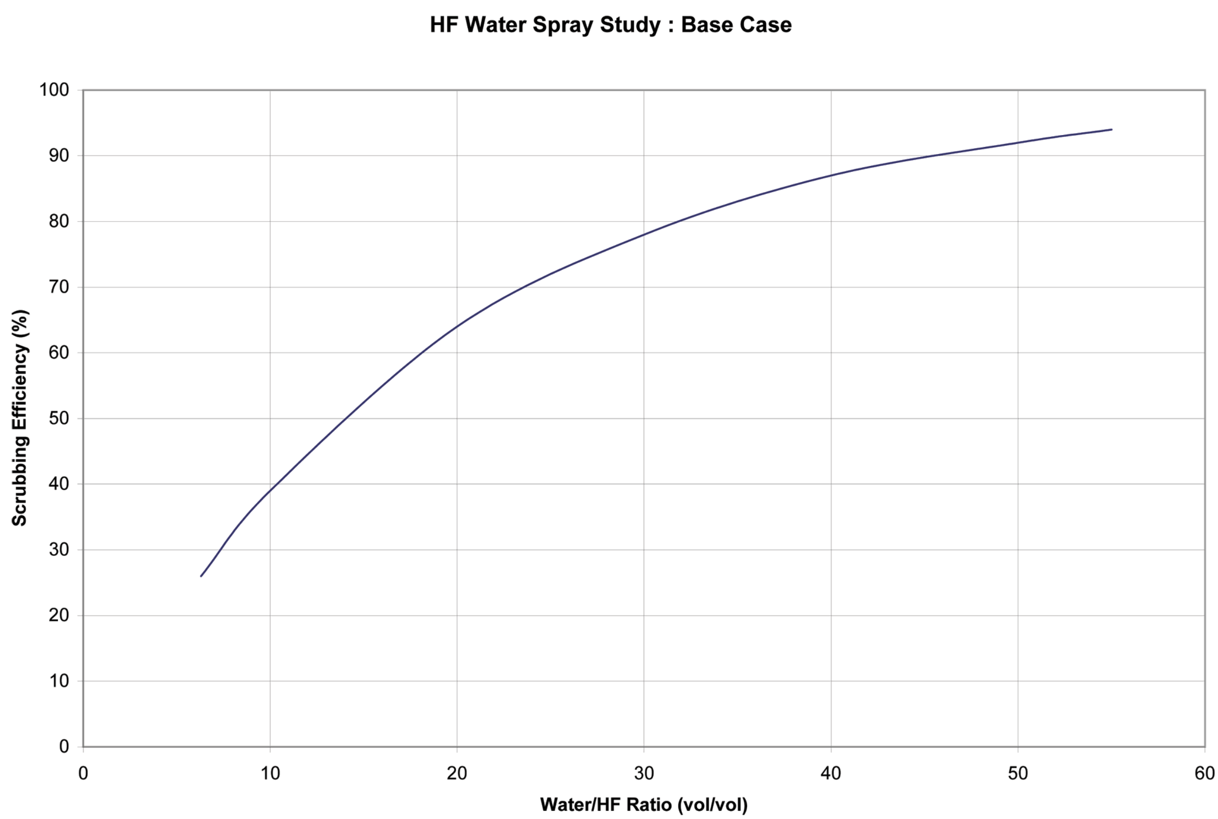


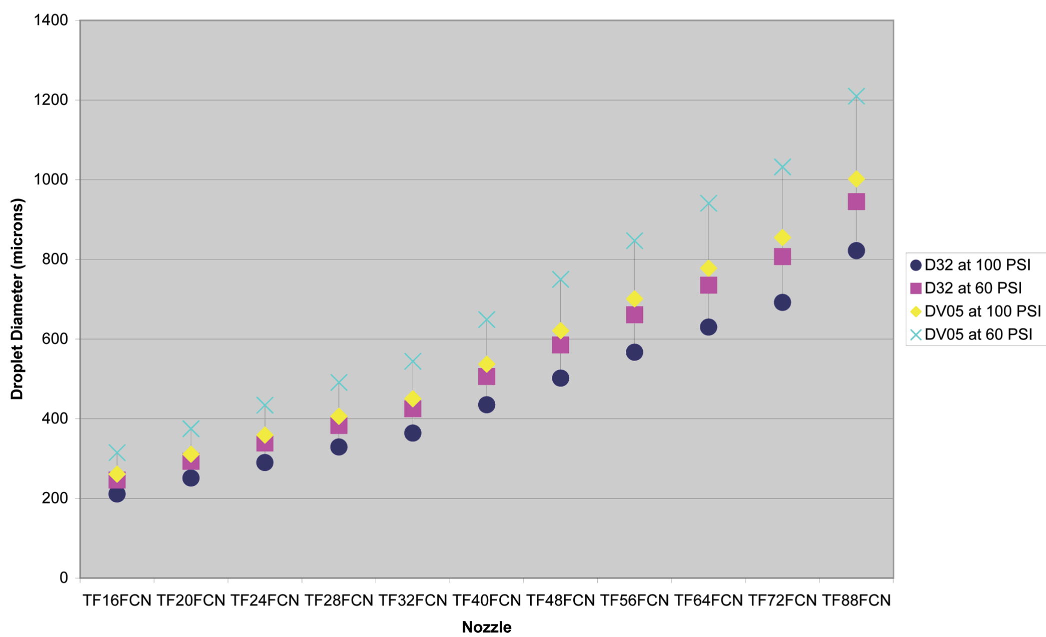
Figure 1. Field HF Water Spray Study, base case

HF Mitigation

TF Series

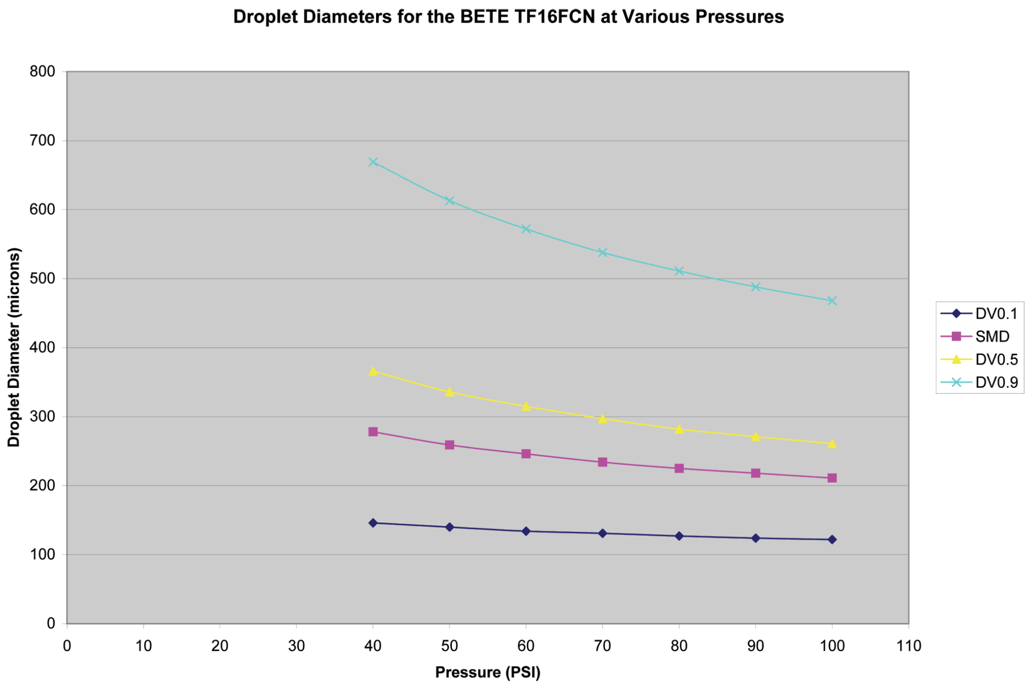
Spray Angle (degrees)	Male Pipe Size	Nozzle Number	Orifice Diameter (in.)	Free Passage Diameter (in.)	Gallons per minute @ PSI		
					40	60	90
90	3/8	TF16FCN	1/4	1/8	10.6	13	15.9
		TF20FCN	5/16	1/8	16.6	20	24.8
	1/2	TF24FCN	3/8	3/16	24.1	29.4	36
		TF28FCN	7/16	3/16	33	40	49
	3/4	TF32FCN	1/2	3/16	42	52	63.7
	1	TF40FCN	5/8	1/4	67	81	99.2
	1-1/2	TF56FCN	7/8	5/16	129	159	194.7

Droplet Size Selection Chart for the BETE TF-FCN Series



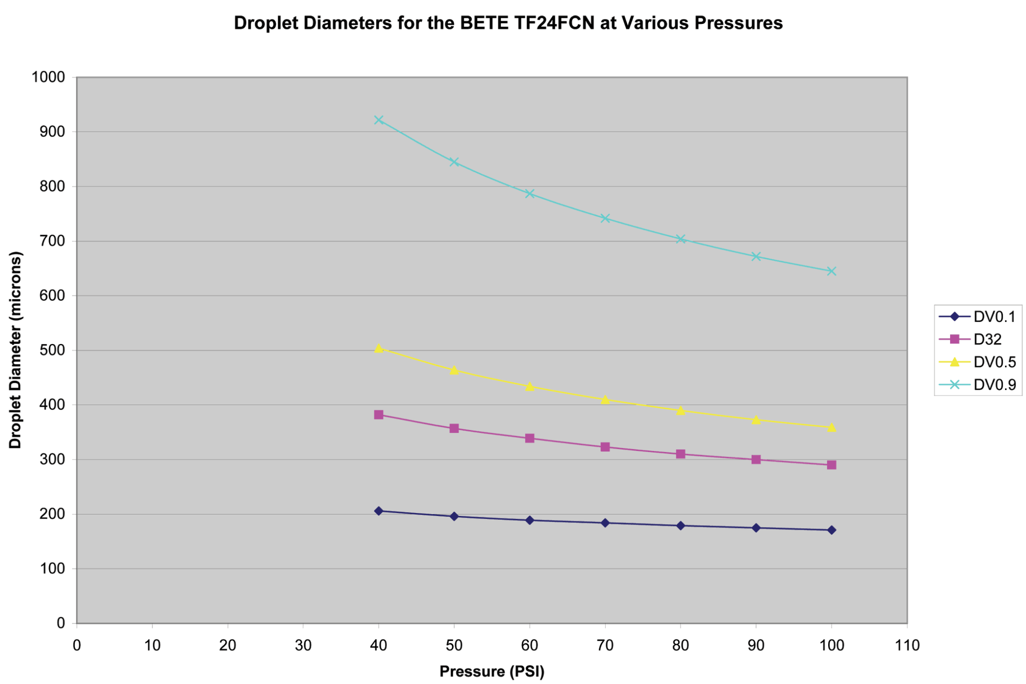
HF Mitigation

TF 16 FCN



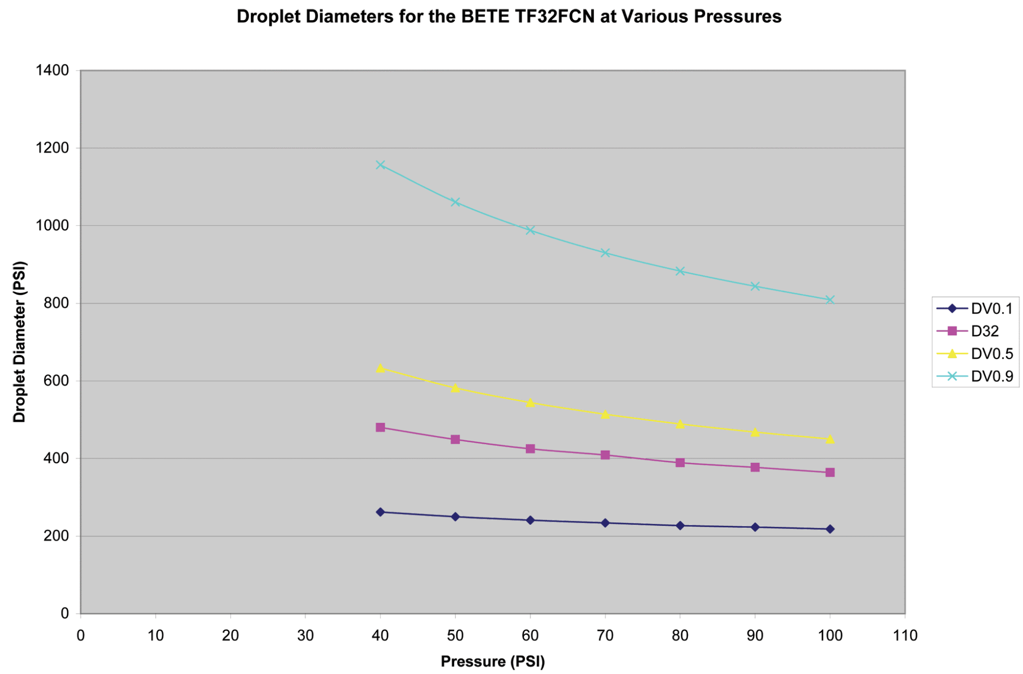
Droplet Diameters as Function of Water Delivery Pressure

TF24FCN



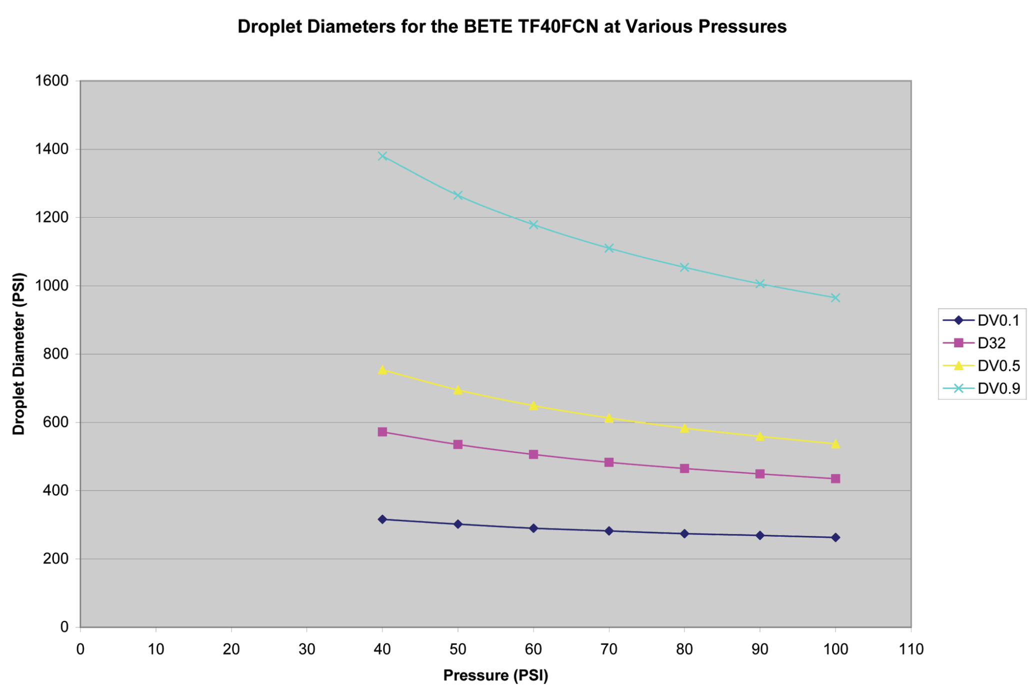
Droplet Diameters as Function of Water Delivery Pressure

TF 32 FCN



Droplet Diameters as Function of Water Delivery Pressure

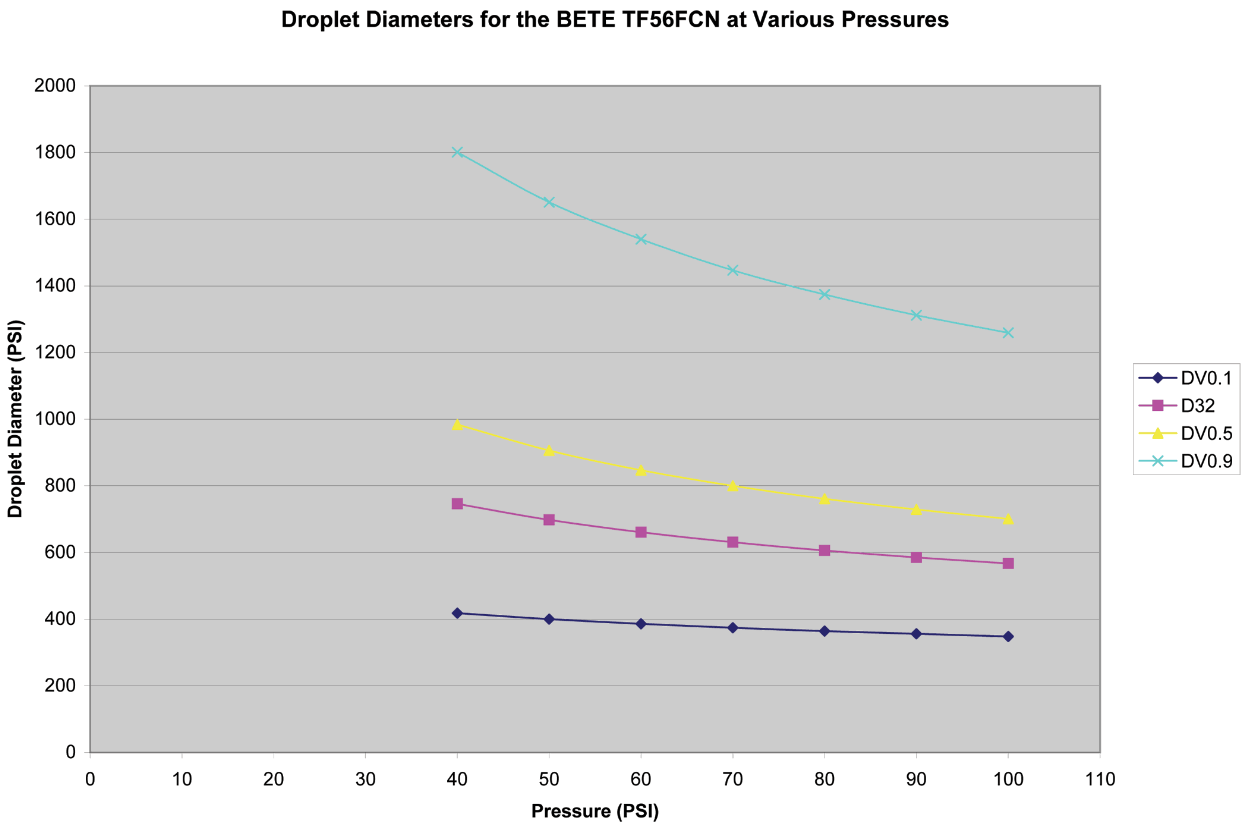
TF 40 FCN



Droplet Diameters as Function of Water Delivery Pressure

HF Mitigation

TF 56 FCN



Droplet Diameters as Function of Water Delivery Pressure

Part II

Practical Considerations for Nozzle Selection in Water Spray HF Mitigation Systems

Practical Considerations for Nozzle Selection in Water Spray HF Mitigation Systems

by
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Abstract

Recent theoretical and experimental studies have shown that appropriately configured water sprays can be highly effective in mitigating the effects of accidental releases of pressurized, super-heated hydrogen fluoride (HF) and alkylation unit acid (AUA) [Fthenakis 1989, 1990; Schatz *et al*, 1989]. Large-scale studies have quantified the impact of numerous variables on HF removal efficiencies. For volumetric water to HF liquid ratios of 6:1 to 40:1, HF removal efficiencies of 35% to 90% have been demonstrated [Schatz *et al*, 1989].

Applying these study results to actual mitigation system design requires an appreciation of the complex interactions between acid mass transfer and nozzle design, operating parameters and nozzle-array placement and configuration. Effects of nozzle design, spray droplet size and spray angle on HF scrubbing effectiveness are discussed.

Additional considerations of wind effects on water spray gas cloud penetration in moderate wind conditions 3.0 to 15.0 meters per second (7 to 24 MPH) are elucidated.

1. Introduction

The report The Effectiveness of Water Spray Mitigation Systems for Accidental Releases of Hydrogen Fluoride prepared by the Industry Cooperative HF mitigation/Assessment Program (1989, hereafter referred to as the "Study") quantified the impact of numerous variables on the HF removal effectiveness of water sprays [figure 1].

Of the number of variables impacting the efficacy pf the HF mitigation investigated within the scope of the Study, three of these variables are particularly sensitive to spray nozzle performance:

- Sauter Mean droplet diameter
- Volumetric ratios (water/HF)
- Placement and configuration of arrays

Generating applicable design specifications for general HF mitigation systems was outside the scope of this Study. Local factors such as risk assessment studies, environmental and regulatory issues, unit size, type and location, existing firewater and spray systems will all impact the final system design.

Applying these study results to the selection of specific nozzle types and array geometries requires an appreciation of the interrelation between nozzle design/operating parameters and nozzle performance in terms of atomization, spray coverage and overall HF scrubbing effectiveness.

When evaluating initial designs for a water spray HF mitigation system. The effect of local winds on the development of spray patterns and spray penetration into the acid cloud must be assessed. Modifications to the array configurations and nozzle spacings considered in the Study may be prudent in order to minimize acid cloud by-passing while maintaining high levels of acid mass transfer.

While it is tempting to reduce the Study's conclusions to a simple rule-of-thumb involving the number of gallons of water to be sprayed per gallon of HF released, the overall HF scrubbing effectiveness is highly sensitive to a number of other variables. Additional trade-offs may be required between the fine spray atomization the Study demonstrated to be effective for high HF removal levels and the nozzle characteristics needed to reduce system complexity, maximize reliability under adverse environmental conditions and resist cross-wind induced spray pattern deformation.

2. Effect of Sauter Mean Droplet Diameter on HF Removal Effectiveness

A nozzle produces a spray composed of a range of droplet sizes (diameters). When we talk of a nozzle producing droplets of a given diameter, we are really discussing a drop size that somehow characterizes the varied droplet sizes making up the spray volume. While there are at least seven different commonly employed definitions used to characterize spray droplet diameters, the **Sauter Mean Diameter** (**D32**) is the best indicator of a spray's performance in processes involving complex interactions with the droplets' surface and volume, such as spray drying, evaporative cooling, dry scrubbing, gas quenching and gas absorption. Sometimes abbreviated to S.M.D. the Sauter Mean is the diameter of a droplet whose ratio of volume to surface area is equal to that of the complete spray sample. It is defined as the cube of the Volume Mean Diameter (DV30) divided by the square of the Surface Mean Diameter (DV20).

2.0.01. $\mathbf{D_{32}} = (D_{V30})^3 / (D_{V20})2$

The Sauter Mean diameter is typically 80% of the Volume Median diameter (DV0.5).

Sometimes abbreviated **V.M.D.** or **M.V.D.,** the **Volume** (**or Mass**) **Median Diameter** (**DV0.5**) divides the volume (or mass) of the spray into two equal halves. Thus, one-half of the total volume (or mass) is composed of droplets smaller than the Volume Median diameter, and half of diameters larger than the Volume Median Diameter. The DC0.5 droplets are often modeled to define the spray envelope for combinations of nozzles and operating conditions.

The Study found a strong correlation between decreasing spray Sauter Mean (D32) droplet diameters and increasing scrubbing efficiencies [figure 2].

Decreasing the D32 from the Base Case 320µm resulted in an increase of scrubbing efficiency from 53% to 72% at a water/HF ratio of 15:1 (vol/vol) [Study, tests 15, 16 &20]. Reduction of the Sauter Mean diameter can be accomplished by several strategies:

- Optimize nozzle design for atomization performance
- Increase water supply pressure
- Decrease orifice diameter
- Increase spray angle

In conditions of moderate wind, these strategies can have adverse impacts on spray penetration into the gas cloud. Significant spray pattern deformation and droplet entrainment can occur; allowing portions of the gas to bypass the spray and reducing the acid mass transfer to the droplets.

3. Factors Influencing Sauter Mean Drop Size

3.1 Nozzle Design

Nozzle design has considerable influence on spray droplet size. Ignoring performance variations within each nozzle type, direct pressure spray nozzles can be ranked as follows (in order of increasing droplet size):

Nozzle Type	Relative D32 (1.0 = spirals)
Spiral Impingement	1.0
Turbine Whirl	1.3
Wide-angle Whirl Tangential	1.35
Disk Whirl	1.7
Flat Fan	2.0
Narrow-angle Whirl Tangential	2.4
Impingement Flat Fan	2.5

[figure 5]

At a given supply pressure, the most cost-effective means of lowering the D32 of a spray is to utilize nozzle designs optimized for atomization efficiency.

The spiral impingement nozzle type produces the finest atomization of any direct-pressure nozzle. Selecting a spiral impingement design over the typical full-cone whirl type will result in a 30-50% reduction in D32 diameters at equivalent flow and pressure conditions. This smaller D32 translates into 2 to 3.3 times the available droplet surface area produced by the whirl nozzle type at equivalent flow and pressure conditions.

BETE Fog Nozzle has been involved in a number of studies and development projects concerning fire and explosion suppression, control and prevention.
We developed the spiral impingement design specifically for these applications. The spiral design is a significantly finer atomizer than the traditional whirl type, producing sprays thirty to fifty percent finer for equivalent flow, pressure and spray angle.

The nozzles are a compact, rugged, one-piece design having no internal plates or disks. The absence of internals makes the spiral design a low-maintenance unit remarkably resistant to clogging.

The design of the "full-cone" spiral nozzle develops concentric dense rings of highly atomized liquid, with unique reduced-pressure inter-cone volumes filled with the more finely atomized liquid. This finely atomized spray presents an extraordinarily large amount of droplet surface area over which acid mass transfer can occur. These fines are very effectively restraining within the inter-cone volumes, allowing for prolonged intimate liquid-gas contact even under adverse wind and thermal convection conditions.

By contrast, whirl nozzles create sprays in which the droplet fines are located at the outer spray cone surfaces. These fines rapidly become de-coupled from the main spray volume and are extremely vulnerable to entrainment by wind and thermal convection. Under even light wind conditions, these fines are thus effectively removed from participation in HF absorption.

At elevated pressures, the reduced pressure zones within the spray pattern produced by the spiral impingement nozzle are significantly enhanced. These larger pressure differentials can reduce the effective angle of the spray and cause the adjacent cones of narrow-angle spiral nozzles to combine.

The spiral nozzles are highly efficient; having discharge coefficients of between 0.94 and 0.97, with exist velocities approaching the theoretical values predicted by Benoulli:

3.1.01 $\mathbf{U} = C_D\ (2gH)^{0.5}$

The Study's authors for the main water spray study component chose the spiral impingement nozzle design. Because of their documented effectiveness in HF mitigation and the clear performance advantages of the spiral over tradition al whirl nozzles, the spiral impingement design is indicated for use in water-pray HF mitigation systems.

3.2 Water Supply Pressure

Droplet size varies **inversely** approximately as the **0.3 power** of the source pressure. Among the various nozzle types, this exponent can easily range from **–0.2 to –0.4.** For the spiral impingement design, a pressure exponent of **–0.3** can be reasonably used. A fifty percent reduction is D32 diameter would require approximately a tend-fold increase in operating pressure for a given spiral impingement nozzle.

Although the D32 diameters can be reduced by increasing the supply pressure at the nozzles, line losses, design and capital costs considerations typically constrain the maximum available pressure in large-scale installations to under 150 psig at the nozzles. Other concurrent uses of the supply lines (fire monitors, hose reels, wash-down lines) will often reduce worst-case supply pressures to 60-80 psig at the nozzles.

3.3 Nozzle Orifice Diameter

Droplet size can vary **directly** as the **0.8 power** of the orifice diameter. There is a wide variation in this exponent among the various nozzle designs. This value can range from **0.3** to **1.2**. Spiral impingement nozzles are characterized by an orifice exponent of 0.8 while traditional whirl nozzles range down 0.5. A fifty percent reduction in D32 can be achieved with an orifice ratio of 1:2:4 for the spiral design. The whirl-type nozzles require up to a 1:4 orifice ratio to achieve an equivalent drop size reduction.

Decreases in D32 diameters achieved by reducing the nozzle orifice diameter will also decrease the flow per nozzle. Additional nozzles need to be provided in order to maintain the design Water/HF volumetric flow ratio.

The nozzles in a water spray system need to be protected from pluggage by entrained particulates (sand, rust scale, algae, invertebrates, etc.) by adequate screening or filtering of the water supply. “Adequate” is generally considered to imply removal of particulates with diameters exceeding 50% of the minimum nozzle passageway (“free passage diameter”).

Providing individual strainers for each nozzle is not a practical strategy for large-scale installations due to maintenance, inspection and cost constrains. The typical approach locates coarse screen strainers at the mains/branch intersections. Somewhat finer screening is provided at the branch/one intersections with the final target screen sizes used to protect the individual array headers. The nozzles are therefore liable to plugging from particulates generated downstream from the final strainer. To prevent external nozzle pluggage at installations within the ranges of mud wasps and other similar nuisance pests, the nozzles should be provided with blow-off protective covers.

Under outdoor field conditions, pluggage and maintenance concerns will generally limit orifice (or more critically, free passage) diameters to the range of 0.125” (BETE **TF 16 FCN**) and 0.187” (BETE **TF 20 FCN**). The large free passage versions of these nozzles have free passages of 0.250” and 0.313” respectively.

3.4 Emitting Spray Angle

Droplet size can vary **inversely** as the **0.25 power of the tangent of the ½ cone angle** for reasonable changes in angle. The spiral impingement design produces the finest sprays when designed for an emitting angle of 120º to 140º. Above 150º, the spirals can evidence a rapid coarsening of the spray. Whirl nozzles also tend to produce the finest sprays within the 120º to 140º range, while limitations inherent to the type generally constrain emitting angles to under 135º.

Decreasing the spray angle from 120º to 90º entails a drop size penalty of approximately 15% for the spiral impingement nozzles.

At pressures above 60 psi, spiral impingement nozzles with emitting angles less than 80º evidence a melding of their component cones. This effect eliminates the reduced-pressure inter-core volumes that are normally filled with droplet “fines.” Most of these fines will migrate into the center volume at higher pressures, but up to 30% can be driven to the outer cone surface. The nozzle becomes effectively a wide-band hollow-cone nozzle.

For this reason, further reduction below 90º in spray emitting angle should not generally be considered an effective strategy for enhancing in-the-field HF scrubbing efficiency when using spiral impingement nozzles.

4. Effect of Nozzle Array Configuration on HF Removal Effectiveness

The Study concluded, "…that up-flow improves the efficiency in the lower range of water/HF ratio, while at higher ratios the effect of up-flow becomes inconclusive or negligible" [Study, p.166 Detailed Report]. The increase in efficiency does not appear to be proportional to the increase in residence time of the droplets within the HF cloud. The Study surmises equilibrium in the acid mass transfer, which may be partially due to the low relative velocity of the droplets during much of their residence within the acid cloud. Fthenakis (1990) indicates lower absorption effectiveness for all directions of sprays other than vertical downward.

The Study also concludes a small detrimental effect on scrubbing efficiency with increasing nozzle elevation above the HF release point [p.167 *ibid*].

Additional effects of miscellaneous geometry changes show that two headers located 5 meters and 10 meters (16'0 and 32'0) downstream of, and 2.4 meters (8'0) above the HF source are nearly as effective as the Base Case (single header at 16'0) as is a dual curtain of up-and-down spraying nozzles at 32'0 distance. The Study showed excessive bypassing of the HF cloud over the spray header (and substantially lower removal efficiency) when both the HF orifice and spray header were located at a 2.4 meter (8'0) elevation. Similarly, bypassing of the cloud through the open areas around the two single-nozzle sprays [Study, tests 19 and 62] led to a compensating effect on scrubbing efficiency [p.168 *ibid*].

Given the increased spray coverage attainable, a vertical downward spray orientation is indicated for the majority of outdoor installations. For the BETE **TF 20 FCN** the vertical down spray orientation penetrates 80% further than the vertical up spray in the 3 meters per second cross-flow investigated by the Study [figures 6, 7].

Nozzles mounted so as to spray vertically upward can be placed to advantage, in conjunction with vertical down arrays, at identified potential point-source leaks and at locations where minimum height clearances require overhead arrays to be mounted at elevations above that which would otherwise be considered prudent.

For HF mitigation systems designed for winds of 3.0 meters per second (7 MPH) and under, a vertical mounting of 2.4 meters (8') above the potential leak source appears reasonable [figure 6] when nozzles with equivalent performance to the **TF 20 FCN** considered in the Study are operated at 100 psi. As shall be discussed, higher design wind speeds may indicate narrowed vertical spacing of the spray headers.

The Study results indicate essentially equivalent scrubbing effectiveness between the spray headers located at 5 meters (16'0) and those 10 meters (32'0) downstream of the HF release point.

The location of the water spray header arrays depends upon the nature of the potential HF release sites, whether they be point source or wide area. Isolated point sources can probably be most easily protected with individual arrays located 5 meters to 10 meters (16'0 t 32'0) about the release sites. Where the number of potential release sites is large, or of an area-wide nature, arrays ranged about the perimeter of the site may be more cost effective.

The Study demonstrated an understandable sensitivity of HF scrubbing effectiveness to acid cloud bypassing; the spray headers should be mounted above the leak elevation. Utilizing two staggered sets of arrays separated horizontally by slightly less than the spray pattern effective diameter will minimize bypassing through the open triangles on either side of the individual sprays [Study, p. 268, Detailed Report].

The Study showed an apparent advantage to nozzle spacing along the headers of 0.6 meters (2'0) and 1 meters (3'0) over the 0.3-meter (1'0) Base Case spacing. It is most probable that air eduction and induced turbulence within the gas field are the primary contributors to this effect. If the selected nozzles can generate an adequately wide spray pattern under design wind velocities, wider nozzle spacing along the headers is indicated.

To minimize bypassing, the spray patterns must show some degree of overlap. For the **TF 20 FCN** studied, a 1-meter (3'0) c.c. spacing yields an overlap of approximately 40%-50% in a 3.0 meters per second (7 MPH) air flow. Adjustments to nozzle spacing must be made for other design wind velocities and effective spray coverage diameters.

5. Effects of Water/HF Volumetric Ratio on HF Scrubbing Effectiveness

For water to HF liquid ratios of 6:1 to 40:1, the Study demonstrated HF removal efficiencies of 25% to 90%. The Study presents scrubbing efficiency data as a function of volumetric water/HF ratios for particular Sauter Mean diameters (160 and 320 microns).

At target HF removal rates of 80% and over (water/HF volume ratios in excess of 40:1), designing for large-scale releases of HF entails the spraying of quite large volumes of water. Provisions must be made not only to reliably deliver this volume to the nozzle at design pressures, but also to collect and treat the HF-contaminated sprayed water. The dedicated storm drains and treatment facilities necessary for this task can be a substantial proportion of the total cost of a large perimeter water-spray mitigation system. Minimizing the volume of water sprayed while maintaining high scrubbing effectiveness becomes an important design goal.

HF mitigation systems designs as site perimeter water-spray arrays can decrease total water volume loads by judicious zoning of the system. While zoning the arrays can decrease the associated system capital outlay considerably, the toxicity of HF argues for a fail-safe control system requiring minimum personnel intervention. The control system needs to assess wind direction and leak source and magnitude as well as accommodate variations in wind speed and direction.

6. Assessing Effects of Deviations from Study Parameters

6.1 General

As shall become apparent in later discussion, site-specific considerations may argue for the selection of a combination of nozzles and operating conditions that will result in D32 diameters substantially in excess of the 320μm and 160μm considered in the Study.

In discussion about the impacts of spray nozzle performance parameters on HF scrubbing effectiveness, reframing the volumetric data to reflect a droplet surface area/HF volume ratio will allow a first-order approximation of HF removal effectiveness when sprays of differing Sauter Mean diameters are considered.

The Sauter Mean diameter is defined such that calculating the droplet surface area produced by a spray nozzle is a straightforward task. In units of square meter surface area produced per cubic meter spray volume:

6.1.01 $\mathbf{A_{spray}} = (6 \times 10^6)/D_{32}$

In English Units of square feet droplet surface area per gallon spayed, this equation becomes:

6.1.02 $\mathbf{A/V} = (2.445 \times 10^5)/D_{32}$

Maintaining a constant droplet surface area (and therefore relatively similar HF scrubbing effectiveness) with sprays of larger Sauter Mean diameters will require more total volume of water to be sprayed. Under these conditions, mass transfer considerations imply that HF scrubbing effectiveness will be understated for moderate increases in spay Sauter Mean diameters.

If, for example, the design parameters include a minimum nozzle free passage of 0.5', the larger orifice diameter required will affect a 43% increase in Sauter Mean diameter to 460µm at the design pressure. Maintaining HF scrubbing effectiveness equal to that of Base Case at 40:1 volume ratio will require approximately a ratio of 57:1. This ratio of water/HF flow will maintain a droplet surface area/HF volume ratio essentially equal to that of the Base Case [figures 3 and 4].

6.2 Gas-phase/Droplet Mass Transfer Considerations

Mass transfer rates are dependent not only on available area but additionally are sensitive to the relative velocity of the droplets through the medium and their resistance time within the medium. Very rapid mass-transfer limited chemical reactions occur in a thin liquid layer at the gas-droplet boundary for drops at rest relative to the gas phase, a vigorous internal circulation develops [Pruppacher and Beard, 1971]. A result of external viscous sheer forces, this internal circulation can increase the mass transfer rate five to ten fold over that of a stagnant drop. The magnitude of this effect is dependent on droplet diameter, decreasing with smaller drop size [Tryoler *et al*, 1971]. The addition of surfactants can entirely eliminate this effect.

Droplets in a spray transfer momentum to the surrounding gas. Sufficient transfer occurs to entrain and impart motion to the gas. Knowledge is far from complete as to how momentum is distributed within a spray pattern; between spray droplets and entrained gas, or as to whether the variation in droplet population within the spray pattern is predictable at various distances from the orifice. The established aerodynamic laws of droplet motion cannot be directly applied to the spray system, as there is considerable flow interference between droplets, and the shape of droplets can be distorted during flight.

Gas entrainment mechanisms at a given distance from the orifice tend to be independent of the spray pattern, being governed principally by the laws of turbulent momentum transfer in gas jets. For sprays of fine droplets, the majority of movement in the spray at the nozzle orifice is converted into the momentum of the entrained gas stream within relatively short distances from the nozzle (*i.e.,* within approximately 1.0 meter).

The total flow of gas associated with the spray increases as the spray broadens on moving away from the orifice in the pattern defined by the spray angle. The degree of entrainment, however, does not depend upon the spray angle entirely, as the droplet population throughout the spray pattern appears a factor of great influence. Since the drop space and size distribution varies with spray type, the gas entrainment occurrence differs for full-and hollow-cone spray patterns of the same spray angle. For a full-cone spray, gas may not penetrate the center of the spray pattern until droplets have traveled quite some distance from the nozzle. For hollow-cone sprays, gas penetration is much more rapid and spray-gas mixing more effective.

Turbulence induced in the gas field by this increased entrainment of gas into the spray augments the mass transfer. This enhancement to the mass transfer can be about 30% [Cliff *et al*, 1978]. Fthenakis uses an enhancement factor of 1.3 for the gas-phase mass-transfer coefficient in his Gas Spray model [Fthenakis and Zakkay, 1990] to produce an almost perfect fit with the experimental data.

It is desirable to know the influence of entrained gas on droplet motion from nozzles, as relative velocity between droplets and the gas is a prime factor in mass transfer rates to the spray [Fthenakis and Zakkay, 1990]. There appears to be some relation between flow rate, operating delivery pressure, cone angle and spray pattern, but no generalized form is available at present. The spray emitting velocity from the nozzle followed by gas entrainment maintains droplet velocities considerably higher than droplet terminal velocities over the time periods where the majority of mass transfer takes place. Terminal velocities of droplets falling in a stream are estimated to be some 15% higher than those of single droplets [Kleinstreuer *et al* (1985)]. As a countervailing effect, droplets moving in the wakes of preceding drops encounter depressed acid concentrations, reducing the mass transfer. There are, thus, inevitable errors in predicting HF scrubbing effectiveness caused by evaluating mass transfer rates based on mean gas velocity or droplet terminal velocities.

The effects of aerodynamic drag will tend to decelerate smaller droplet diameters more rapidly than larger droplets, thereby suppressing the mass transfer rate. At larger droplet diameters, the effects of drag on droplet velocity are reduced, at a cost of a reduction in residence time and available droplet surface area. The entire HF mitigation process is a set of complex interactions and is further complicated by site specific variables such as wind conditions, surface roughness, structural obstructions and topography [Diener, R., (1989)]. From the foregoing, it is clear that maintaining a reasonably high relative velocity between the water droplets and gas field is an important design criterion for achieving high HF scrubbing effectiveness.

6.3 Wind Effects On Spray Performance

6.3.1. Spray Pattern Deformation

Most of the relevant Study tests were conducted in an air stream moving at 3.0 meters per second (7 MPH). Applying the Study results to higher air stream velocities requires careful consideration of the interactions between the water spray and the moving air stream. At the higher wind velocities likely to encounter more installations, other factors of spray performance become predominant. Even for the largest nozzle tested in the Study (BETE **TF 20 FCN**) at 100 psi and a D32 of 320μm, severe pattern deformation occurs at wind velocities above 10meters/second (22 mph). In 10 meters per second wind, vertical penetration of the spray is reduced to 1.5 meters (5'). At 15 meters per second (34 MPH) vertical penetration is further reduced to 1.2 meters (4') [figures 8, 9].

6.3.2. Acid By-passing and Induced Turbulence

Minimizing acid cloud bypass under these conditions would imply stacked arrays at vertical spacing well below the 2.5 and 5.0 meters (8'0 and 16'0) considered by the Study. Being also affected by the deceleration due to gravity, the upward spray is subjected to a larger degree of deformation than the vertical downward orientation [figure 7].

In the absence of significant sources of turbulence, the rapid entrainment of spray into the air stream reduces the relative velocity of the majority of droplets to near zero, substantially reducing acid mass transfer, as the cloud is advected down-wind. Any site feature that promotes turbulence in the acid cloud is expected to some degree to increase both the effective spray penetration of the cloud as well as enhance the acid amass transfer. Buildings, structural obstructions, terrain, local sharp temperature differentials and surface roughness will all contribute to this effect. The contributions will, of course, be highly variable and very sensitive to wind direction and velocity. Absent validated site modeling techniques, the prudent approach is to design an HF mitigation system that can achieve the target mitigation level without relying on the additional positive effects on scrubbing efficiency of site-specific characteristics.

The Study demonstrated the sensitivity of HF scrubbing effectiveness to bypassing. At wind velocities of 5 meters per second (10 MPH) and above, acid cloud bypassing due to reduced spray penetration is probably the most important limiting factor in achieving target removal levels. Under these conditions, promoting spray penetration becomes the primary nozzle selection criteria, placing the drop size performance secondary.

Fthenakis (1990) has shown the importance of the gas-phase mass transfer coefficient and gas field turbulence in predicting HF removal rates. It is reasonable to surmise that the combined effects of vigorous internal droplet circulation, increased gas field turbulence and acid cloud penetration associated with rapidly moving larger droplets can partial offset the reduction in simple droplet surface area produced by finer sprays. Because of the inter-relation of the acid mass transfer rate and droplet relative velocity, the larger drop sizes required for cloud penetration should evidence scrubbing efficiencies well above those predicted when based only on the total droplet surface area associated with the water spray.

Similar considerations are particularly apparent in the design of deluge protection system for offshore drilling and production platforms. Recent work undertaken at BETE indicates that when spiral impingement nozzles are utilized, an unexpectedly large increase in D32 droplet diameter is permissible if penetration of the fire plume is achieved. Study conditions posit a 15 meters per second (34 MPH) wind velocity.

6.4 Increasing Cloud Penetration

6.4.1. Spray Orientation

Given the increased susceptibility of an upward water spray to cross-flow induced pattern deformation, a vertical downward spray orientation is indicated for the majority of outdoor installations. For the BETE **TF 20 FCN** tested in the Study, the vertical down spray will penetrate 3.0 meters (10’0) as compared to the 1.7 meters (5’6”) of the vertical up spring in a 3 meters per second cross-flow [figures 6, 7]. Nozzles mounted so as to spray vertically upward can be placed to advantage, in conjunction with vertical down arrays, at identified potential point-source leaks and at locations where minimum height clearances require the overhead arrays to be mounted at elevations above that which would otherwise be considered prudent.

6.4.2. Spray-Emitting Angle

Reducing the spray-emitting angle will also enhance cloud penetration. This is due both to the increased droplet sizes attendant on the narrowed angle and the larger droplet velocity component normal to the cross-flow. Decreasing the spray angle from 120º to 90º entails a drop size penalty of approximately 15% for the spiral impingement nozzles. Spray penetration at 100 psig for the 90º **TF 20 FCN** studied is increased 43% over the 120º configuration at 3.0 meters per second, 67% at 10.0 meters per second and 40% at 15.0 meters per second cross-slows [figures 6,8-12].

For the larger drop size distributions associated with larger nozzle flow capacities, adequate spray penetration is sustainable at emitting angles of 120º and above [figures 15, 14]. The larger spiral nozzles are often configured with three-spiral “turns.” Each succeeding “turn” produces a narrower angle spray cone. For a typical larger 120º spiral nozzle, the three “turns” produce spray cones of 120º, 90º and 60º. Special three-turn 150º wide-angle spirals are also available, with component cones of 150º, 100º and 60º. In all cases, the inner narrow-angle cones will demonstrate increased cloud penetration for the reasons enumerated above.

6.4.3. Droplet Diameter

Increasing the nozzle orifice diameter increases the degree of cloud penetration by several mechanisms. The most direct effect is an increase in the spray drop size distribution resulting in reduced drag on the droplets. Increasing the orifice diameter to 0.875” from the 0.313” of the **TF 20 FCN** results in a D32 of 650 microns at 100 psig. Further up-sizing to an orifice diameter of {88/64} yields a D32 of 880 microns at 100 psig. Cloud penetration is 15 meters per second (34 MPH) cross winds increases over 300% for these larger nozzles [figures 13, 16].

The second mechanism increasing spray penetration is the eduction of air along the cones’ outer surfaces. As discussed previously, this educted air stream reduces the droplet drag by reducing the apparent velocity differential experienced by the droplets. Total air volume educted is dependent on total sprayed volume and is sensitive to array spacing and nozzle density along the component headers. The greater the nozzle spacing, the greater mass of air educted. The larger effective coverage attainable with larger nozzles allows for greater spacings and larger gross volumes of educted air.

Increasing the droplet size distribution will have a negative effect on HF scrubbing effectiveness at given water/HF volume ratios. Sizing the design system flow to maintain the droplet surface area/HF volume ratio associated with the Study volume/volume results should allow for substantially equivalent HF removal effectiveness. For moderate increases in droplet size distributions, the positive effects of induced gas field turbulence and high relative droplet/gas velocities may result in equivalent HF scrubbing effectiveness at lower droplet area/HF volume ratios. Quantifying these effects requires further study.

7. Conclusions

Water sprays can be an effective technique for mitigating the effects of accidental releases of HF and AUA.

The performance advantages of the spiral impingement nozzle design over the tradition whirl type nozzle indicate this design for water spray HF mitigation systems. To maximize reliability under field operational conditions, special spiral configuration with minimum free passage diameters f0.25 to 0.5 should be utilized.

A vertical down spray configuration yields greater spray coverage and resistance to crosswind induced pattern deformation with little or no decrease in HF scrubbing effectiveness over the vertical upward orientation.

In order to effectively deliver the atomized water into the acid cloud, specific site conditions and system design criteria may require that deviations be made from the configurations detailed in the Study. Decreased spray coverage and penetration in moderate winds require closer vertical and horizontal nozzle and array spacings in order to minimize acid cloud by-passing.

Careful selection and sizing of spiral impingement nozzles can result in high HF scrubbing effectiveness even in adverse site environments. Moderate increases in Sauter Mean droplet diameters can significantly enhance cloud penetration in moderate wind conditions.

Decreasing the spray angle to 90º, increasing the orifice diameter and operating at reduced water supply pressure increase spray penetration into cross winds. These strategies reduce acid cloud by-passing and allow for larger vertical spacings of individual headers.

With careful matching of nozzle performance and design site wind conditions, nozzle coverage diameters can be maximized, allowing wider nozzle spacing along spray headers.

Restating the water/HF ratios investigated in the Study in terms of droplet-surface area/HF volume ratios allows first-order comparisons between nozzles of differing Sauter Mean diameters. Larger water/HF volume ratios are required to maintain design HF scrubbing effectiveness when larger nozzles or lower water pressures are used. Additional study is required to quantify the effects of these nozzle-related parameters on HF scrubbing effectiveness under conditions of moderate winds.

8. Acknowledgements

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The Base Case

Down flow, single curtain
No additives
Saunter Mean Droplet Diameter of 320 microns
Spray 16 feet downstream of acid orifice
Acid orifice elevation at 3 feet
Spray header elevation at 8 feet
Eight (8) spray nozzles
No steam dispersion of acid
Acid pressure of 60 psig
Acid temperature of 100ºF
Air velocity of 3.0 meters per second

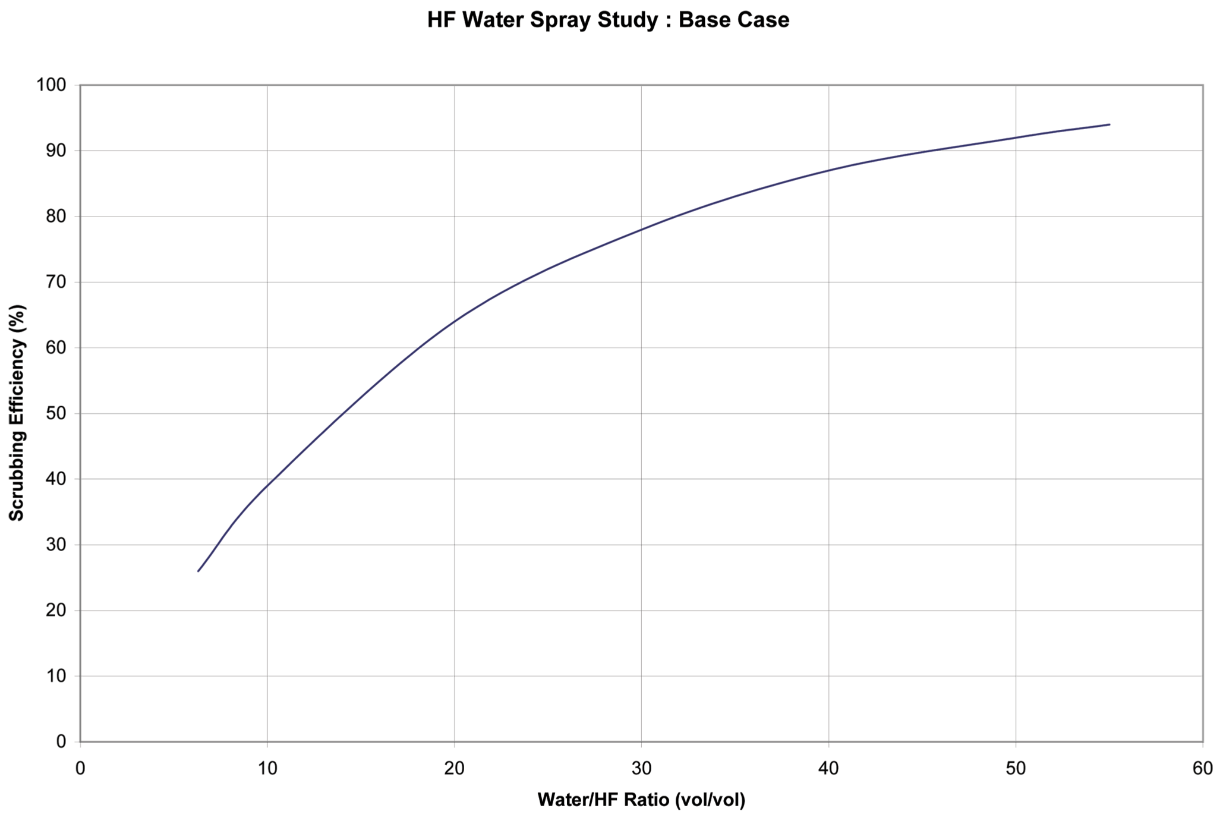


Figure 1. Field HF Water Spray Study, base case

HF Mitigation

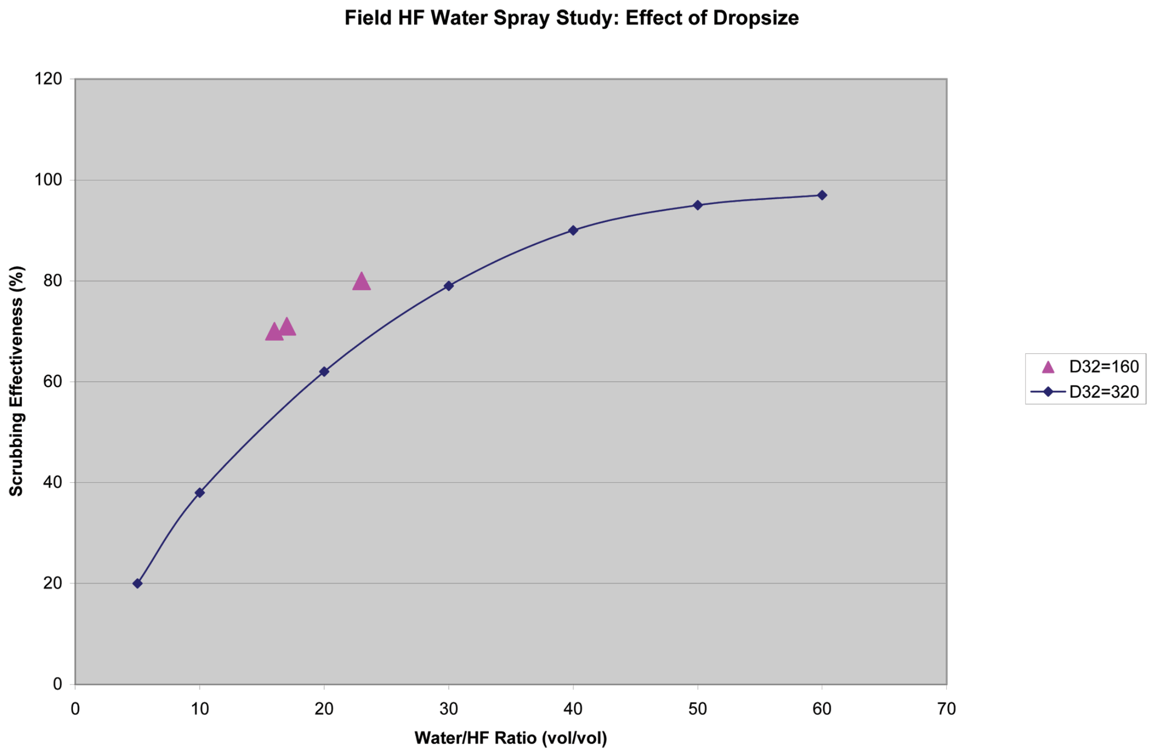


Figure 2: Field HF Water Spray Study: Effect of Drop size

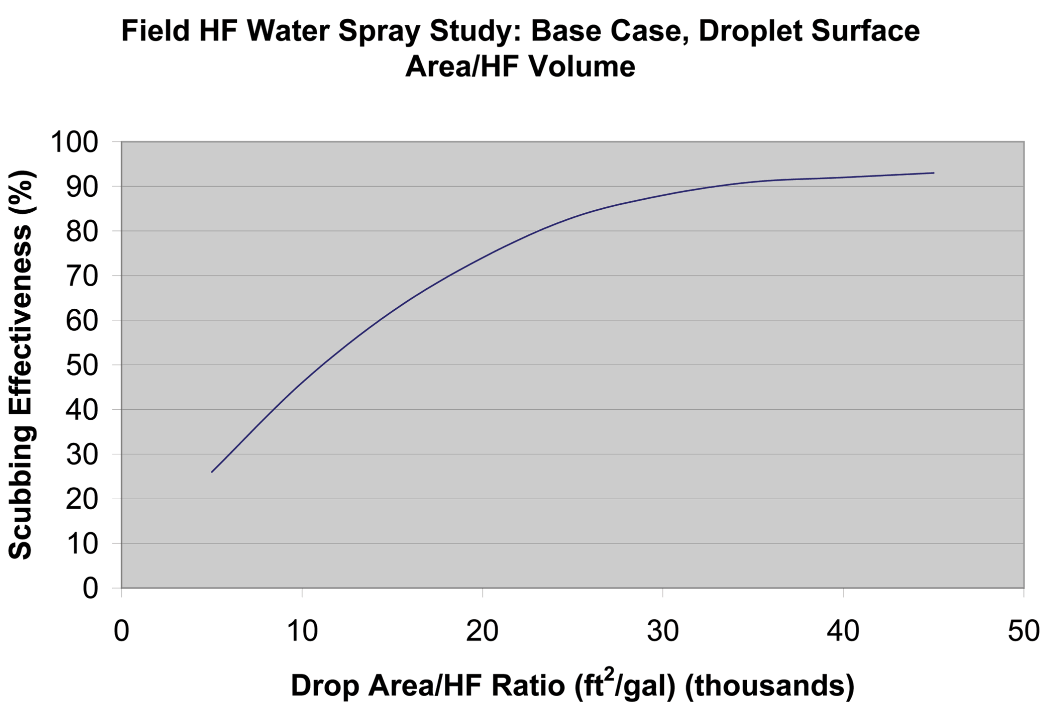


Figure 3: Field HF Study: Drop Area/HF Volume Ratio

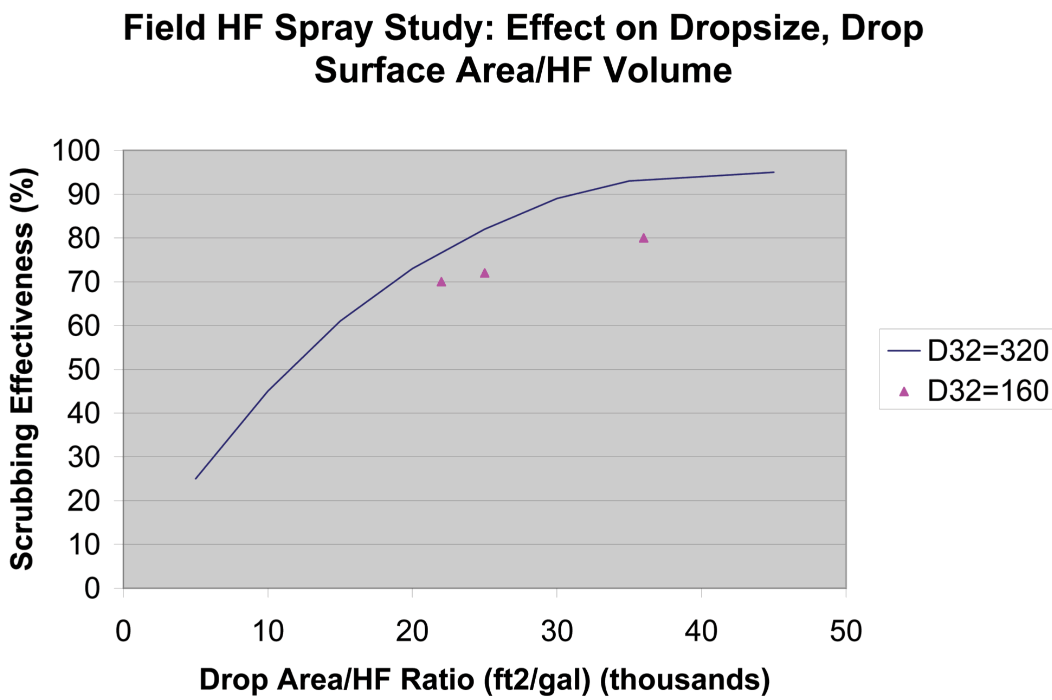


Figure 4: Field HF Study: Drop Area/HF Volume, 160 microns

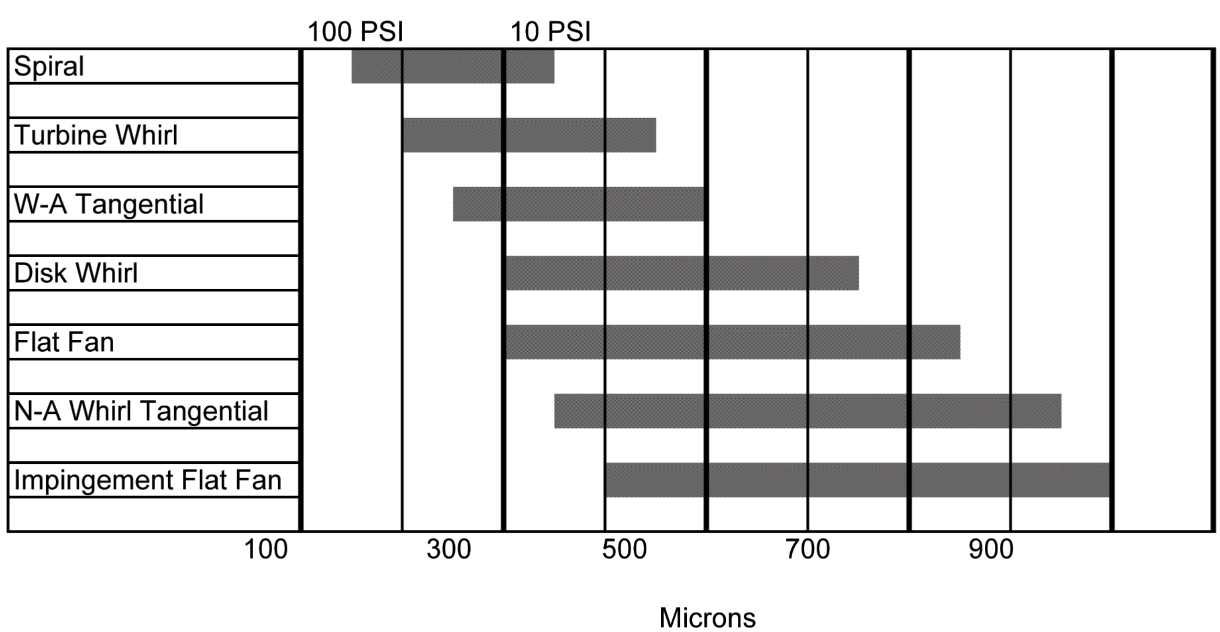


Figure 5: Relative Drop sizes for the Various Nozzle Types

TF20FCN at 100 psi
DV0.5=311 Microns
DV0.9-558 Microns
9.8 ft/s Cross Flow

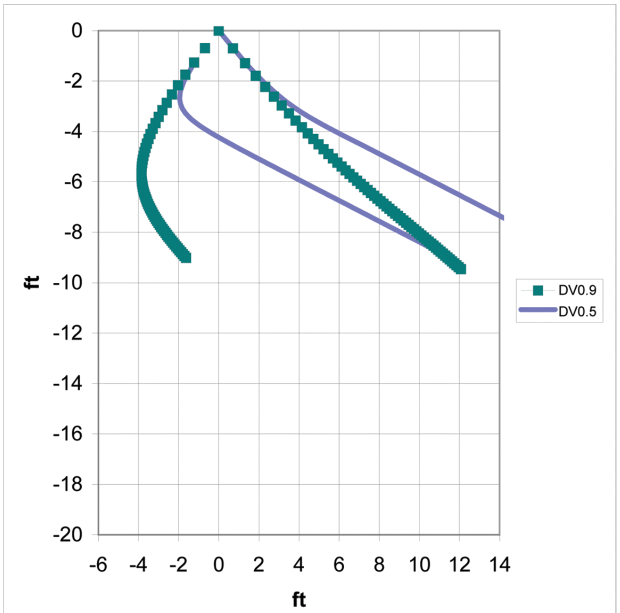


Figure 6: TF 20 FCN at 100 psi in 3.0 mps cross flow

TF20FCN at 100 psi
DV0.5=311 Microns
DV0.9-558 Microns
9.8 ft/s Cross Flow

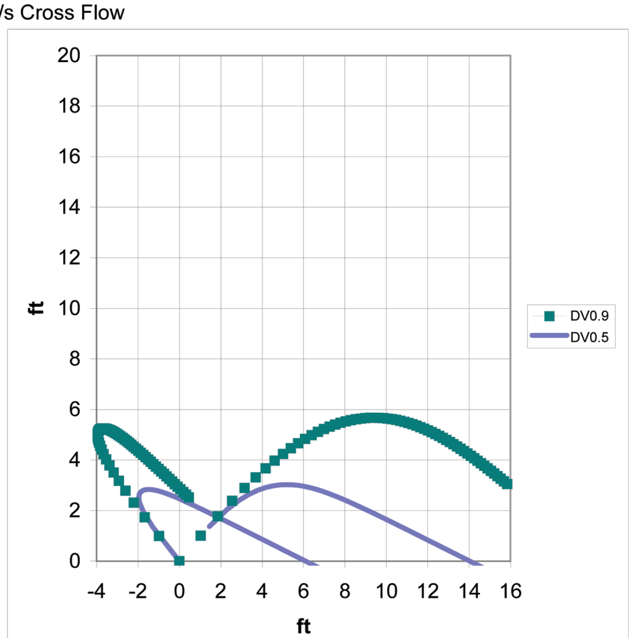


Figure 7: TF 20 FCN at 100 psi (up) in 3.0 mps cross flow

TF20FCN at 100 psi
DV0.5=311 Microns
DV0.9-558 Microns
32.8 ft/s Cross Flow

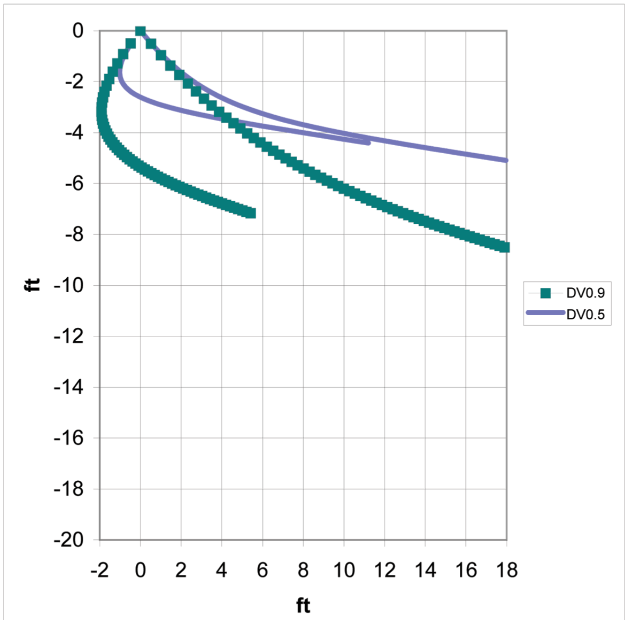


Figure 8: TF 20 FCN at 100 psi in 10.0 mps cross flow

TF20FCN at 100 psi
DV0.5=331 Microns
DV0.9-558 Microns
49.2 ft/s Cross Flow

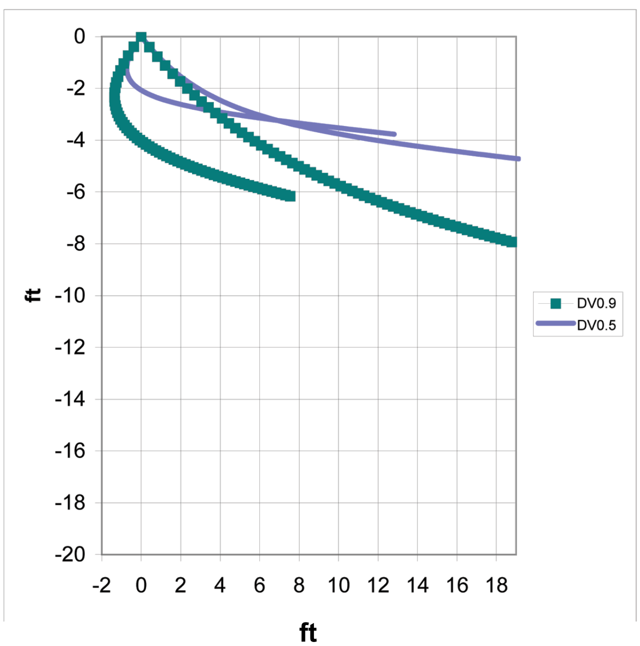


Figure 9: TF 20 FCN at 100 psi in 15.0 mps cross flow

TF20FC at 100 psi
DV0.5=271 Microns
DV0.9-486 Microns
9.8 ft/s Cross Flow

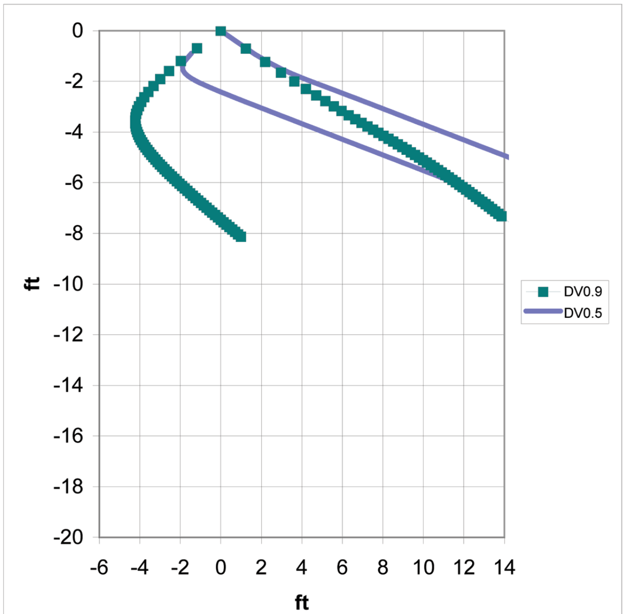


Figure 10: TF 20 FC at 100 psi in 3.0 mps cross flow

TF20FC at 100 psi
DV0.5=271 Microns
DV0.9-486 Microns
32.8 ft/s Cross Flow

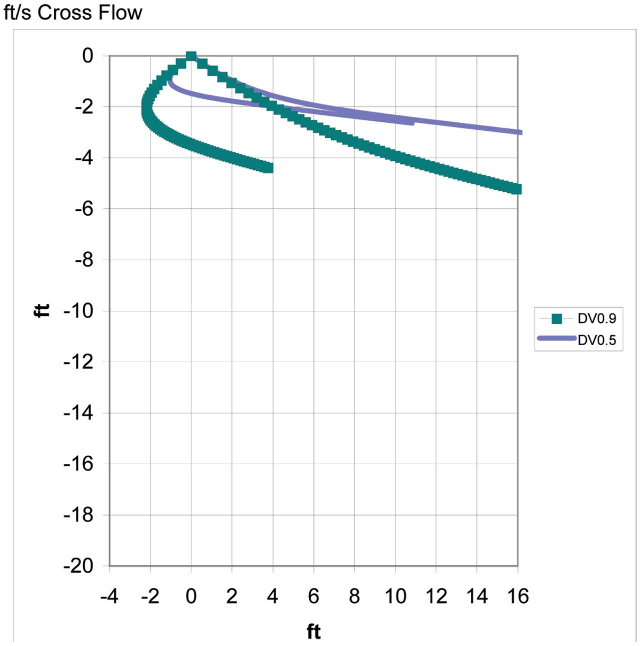


Figure 11: TF 20 FC at 100 psi in 10.0 mps cross flow

TF20FC at 100 psi
DV0.5=271 Microns
DV0.9-486 Microns
49.2 ft/s Cross Flow

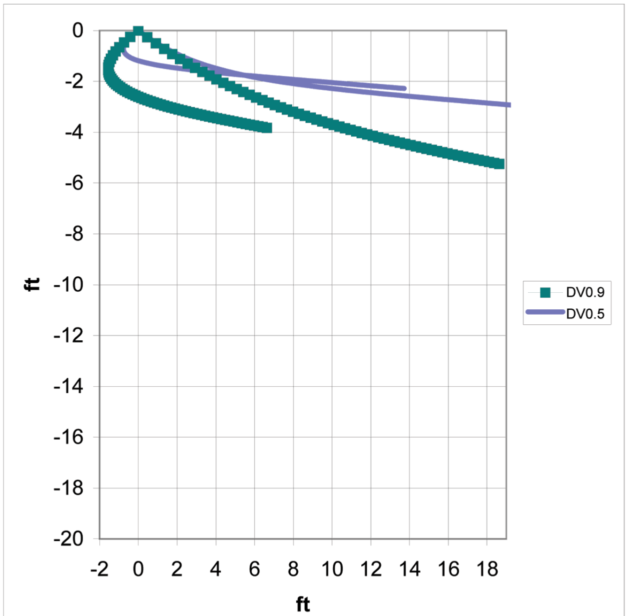


Figure 12: TF 20 FC at 100 psi in 15.0 mps cross flow

TF56FCN at 80 psi
DV0.5=761 Microns
DV0.9-1374 Microns
32.8 ft/s Cross Flow

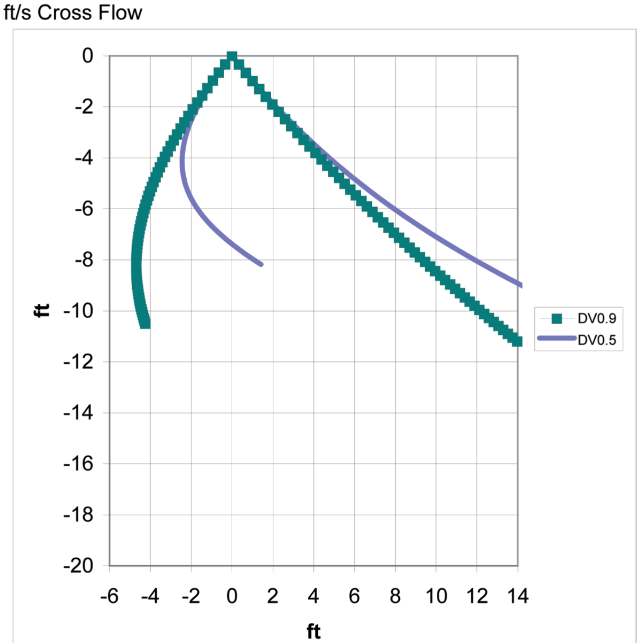


Figure 13: TF 56 FCN at 80 psi in 10.0 mps cross flow

TF88-150 at 80 psi
DV0.5=976 Microns
DV0.9-1762 Microns
49.2 ft/s Cross Flow

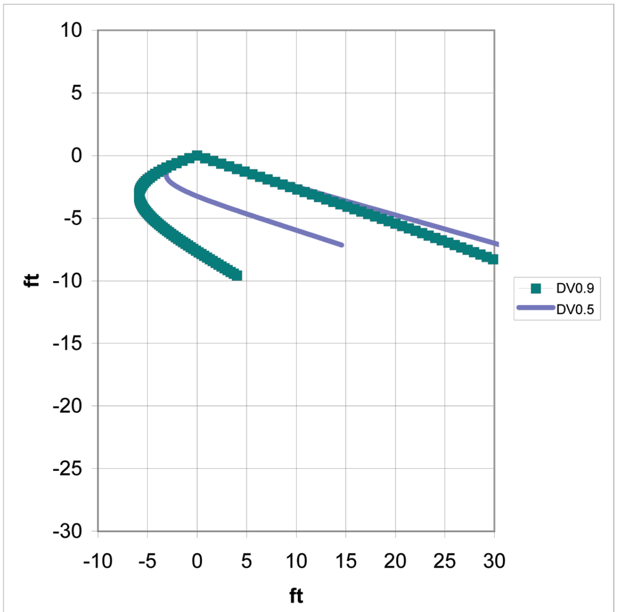


Figure 14: TF 88-150 at 80 psi in 15.0 mps cross flow

TF56FC at 100 psi
DV0.5= 611 Microns
DV0.9= 1097 Microns
49.2 ft/s Cross Flow

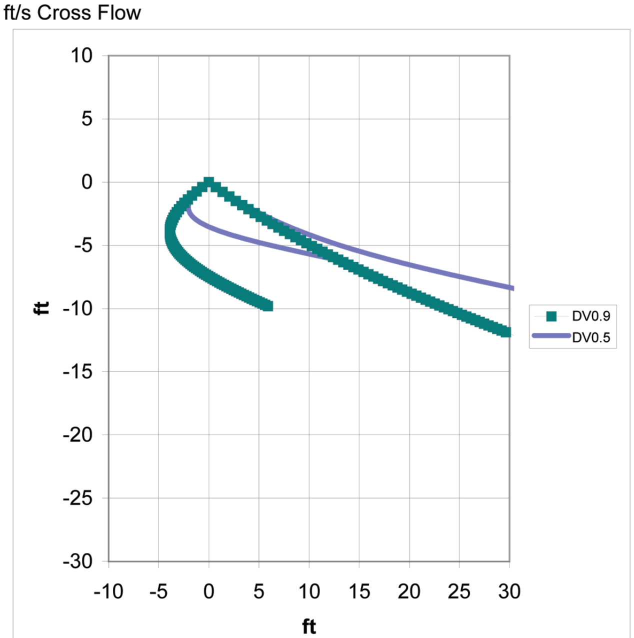


Figure 15: TF 56 FC at 100 psi in 15.0 mps cross flow

TF88FCN at 80 psi
DV0.5= 1088 Microns
DV0.9= 1964 Microns
49.2 ft/s Cross Flow

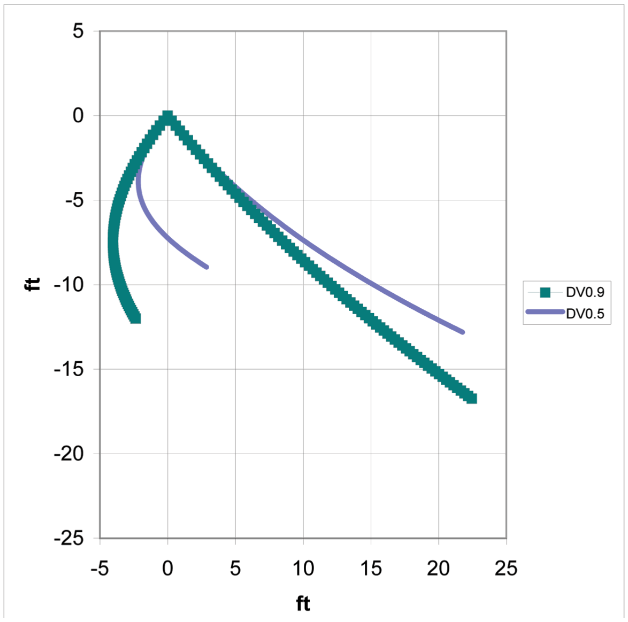
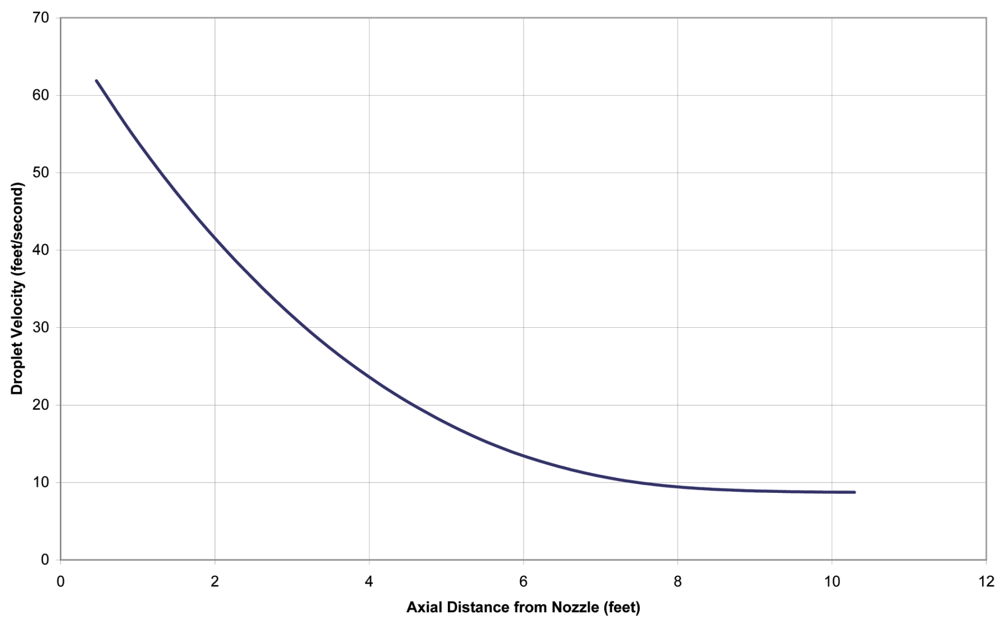


Figure 16: TF 88FCN at 80 psi in 15.0 mps cross flow

Appendix A

Droplet Velocity
Technical Data

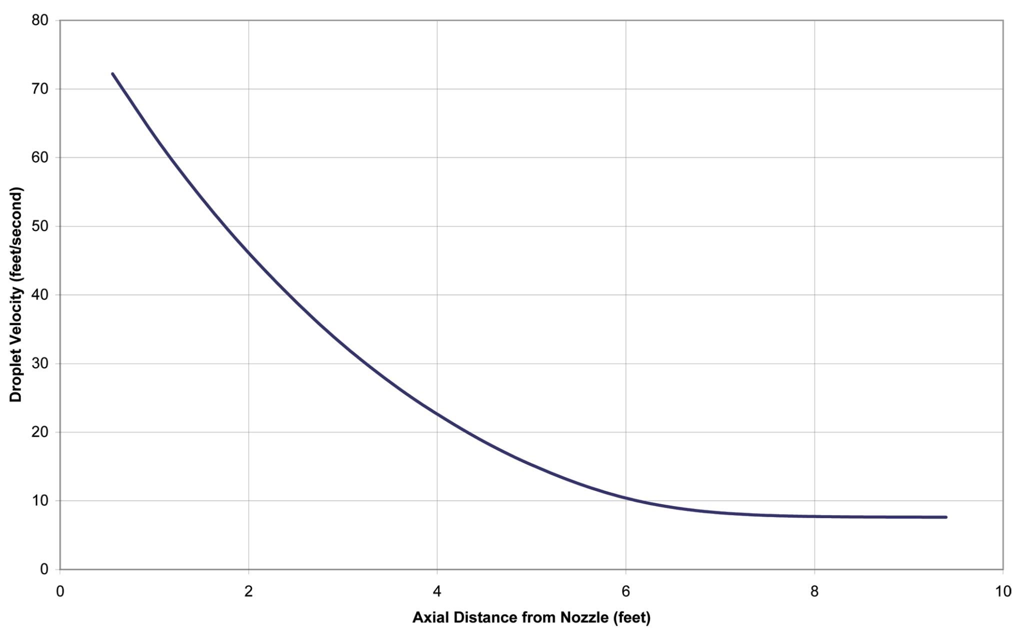
Droplet Velocity for the TF16FCN Spraying Vertically Down at 40 PSI and DV0.9 = 669 Microns



TF 16 FCN

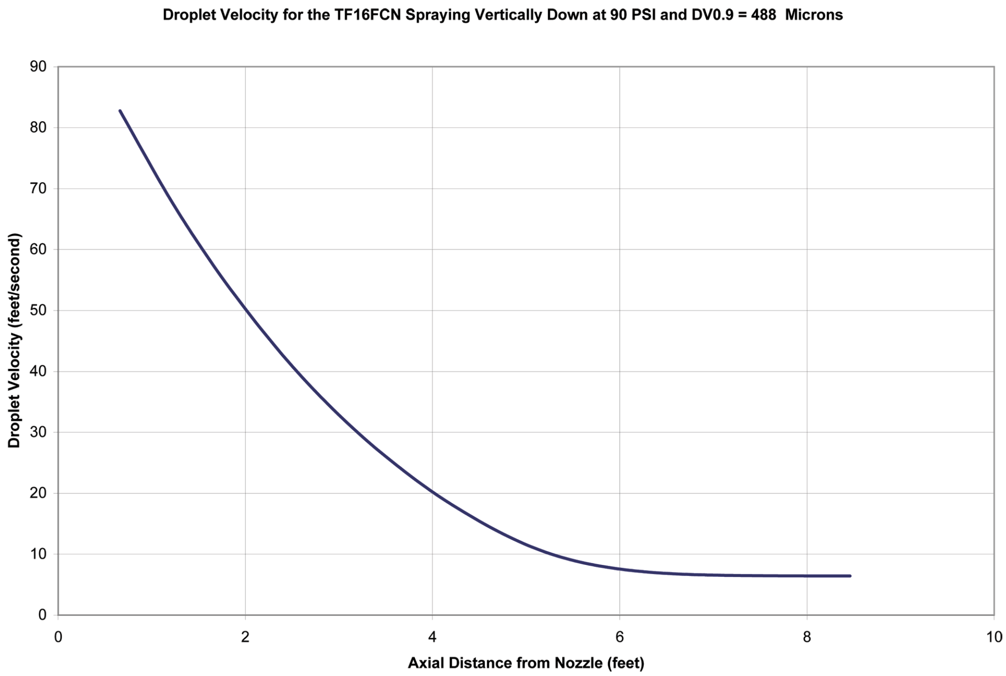
Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter

Droplet Velocity for the TF16FCN Spraying Vertically Down at 60 PSI and DV0.9 = 572 Microns



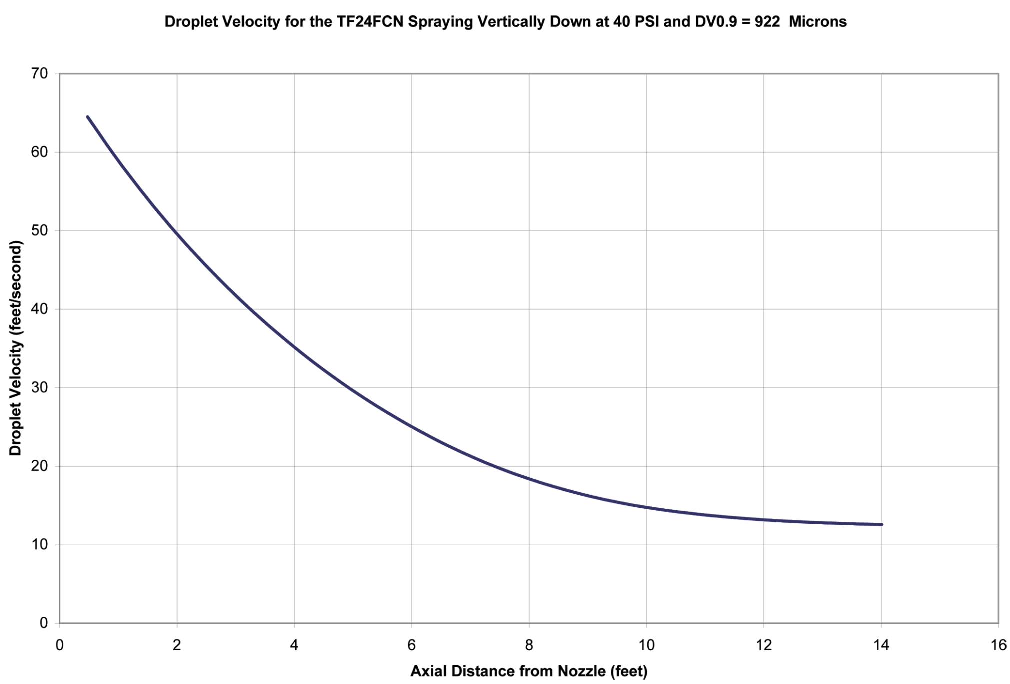
TF 16 FCN

Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter



TF 16 FCN

Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter

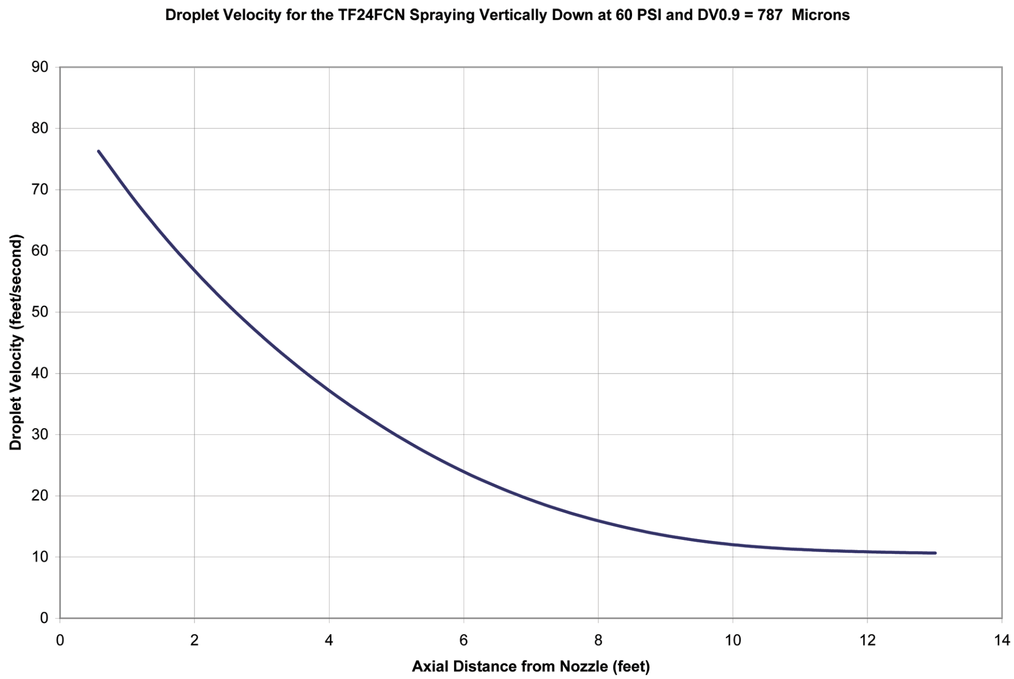


TF 24 FCN

Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter

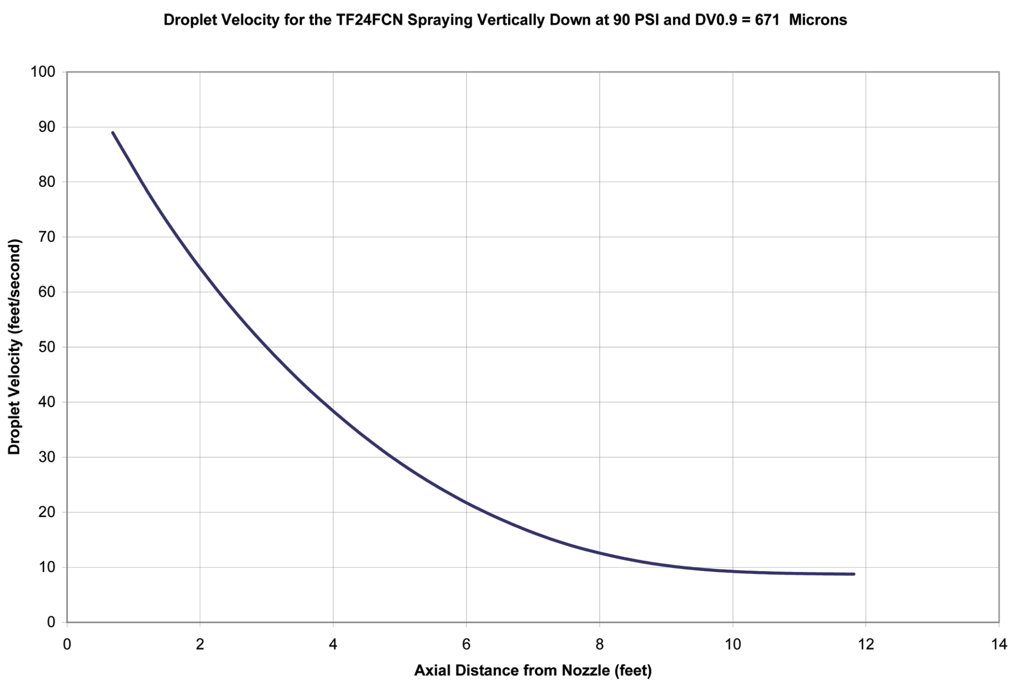
HF Mitigation

TF 24 FCN

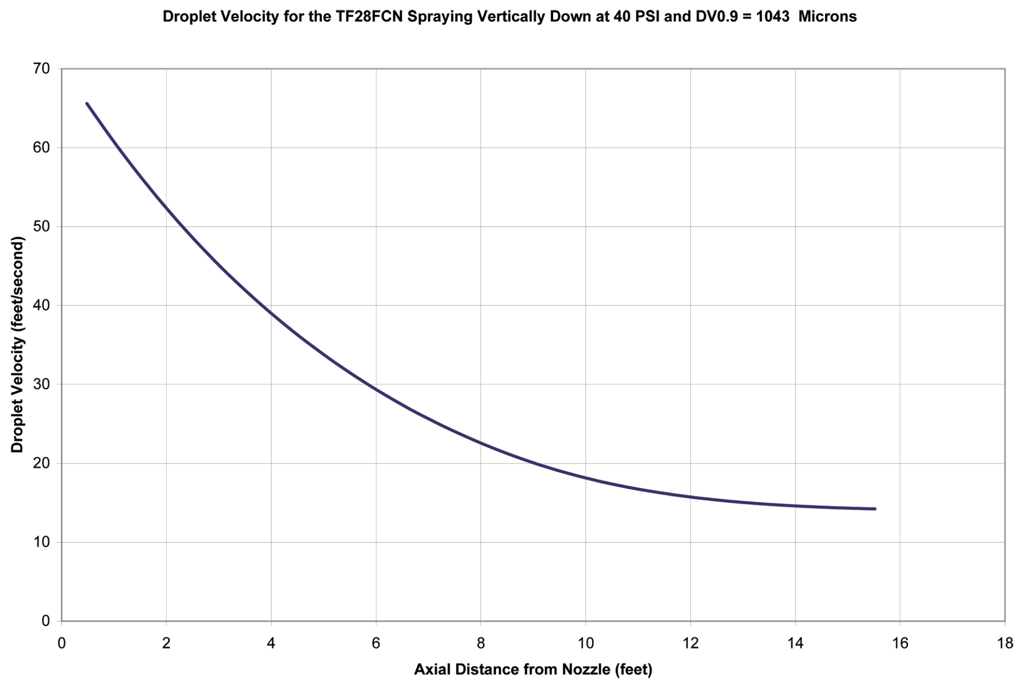


Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter

TF 24 FCN

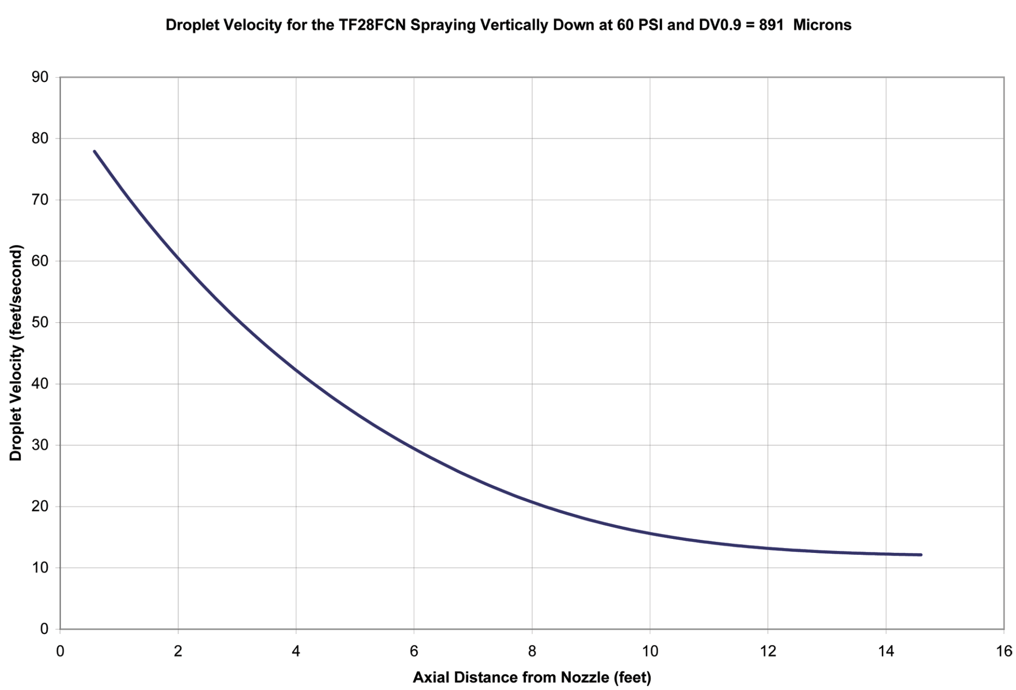


Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter



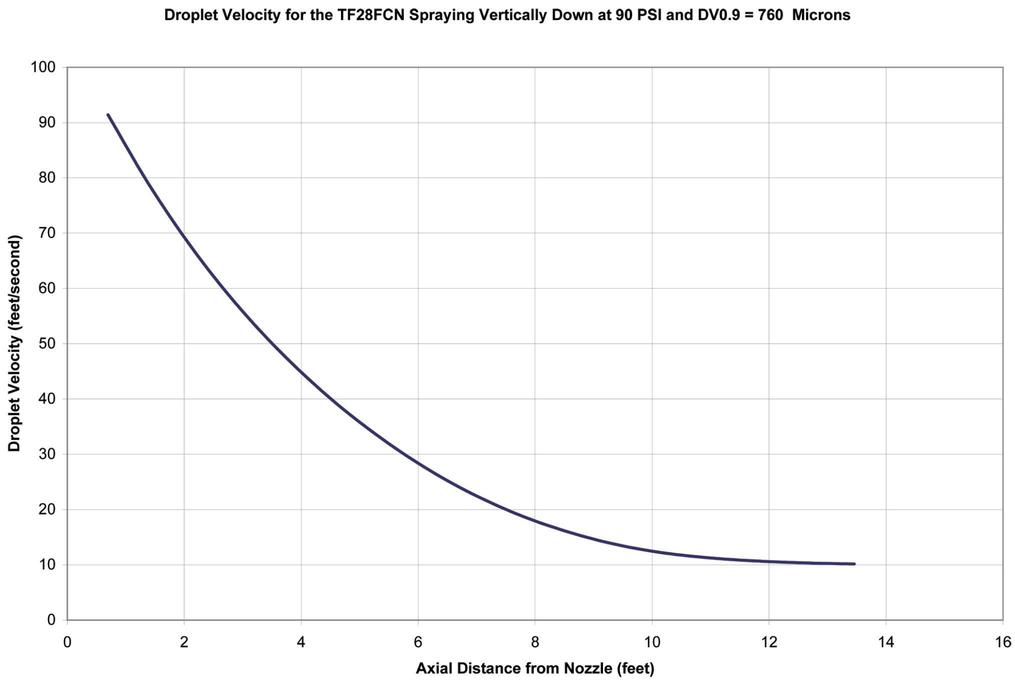
TF 28 FCN

Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter



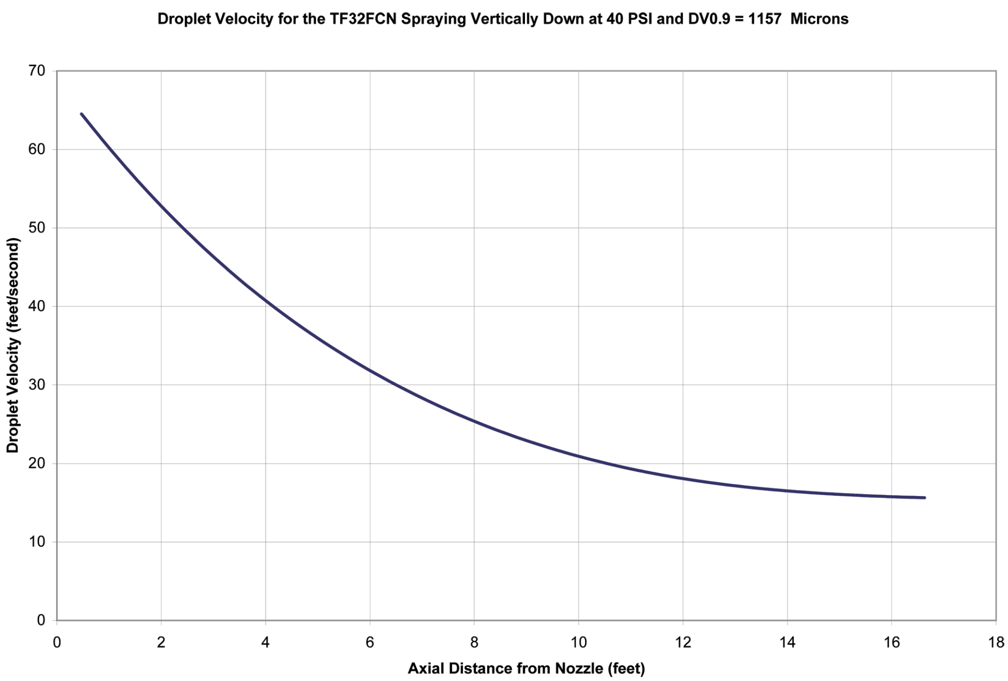
TF 28 FCN

Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter



TF 28 FCN

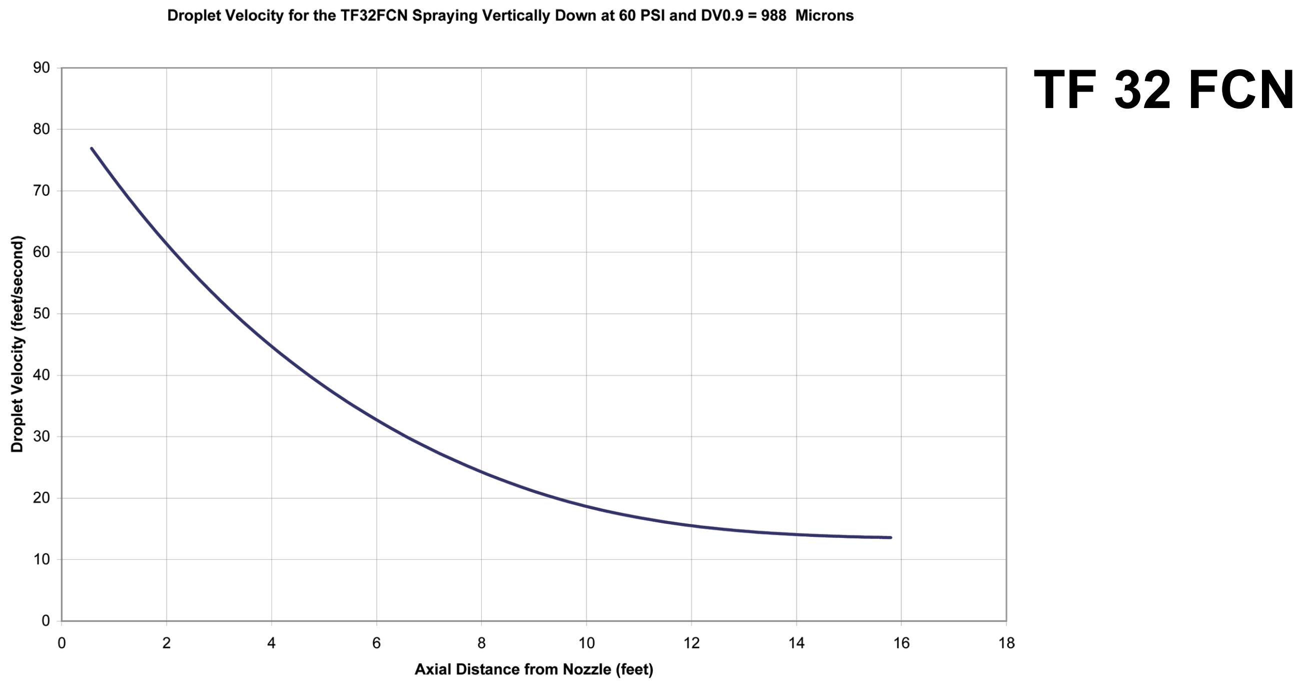
Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter



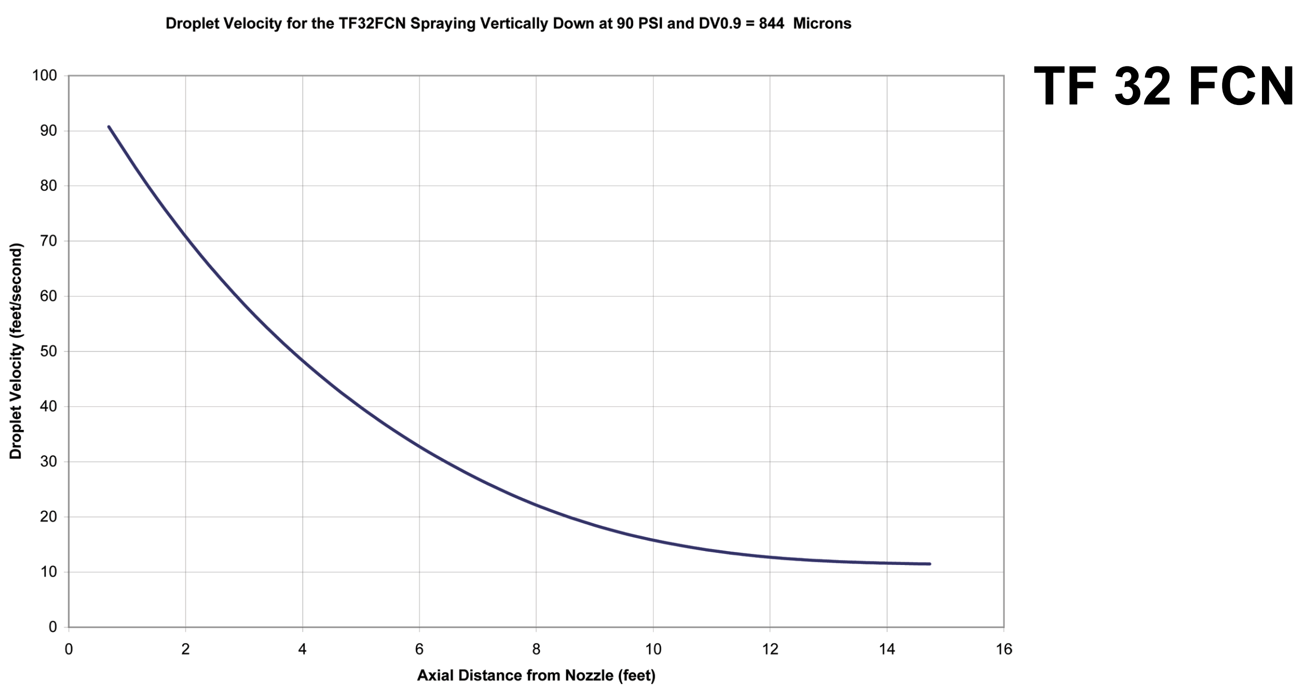
TF 32 FCN

Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter

HF Mitigation

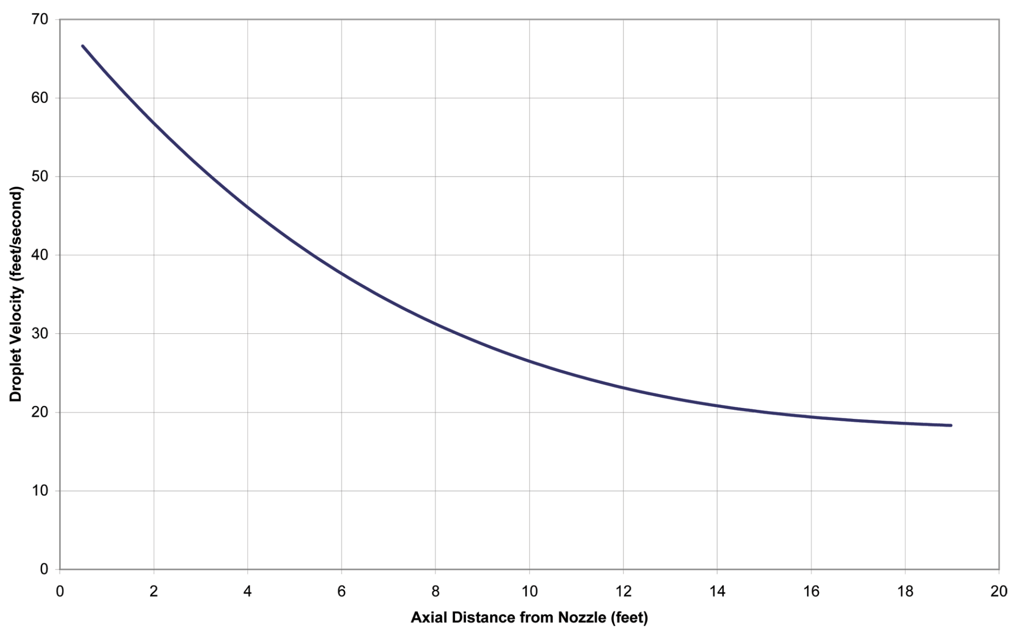


Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter



Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter

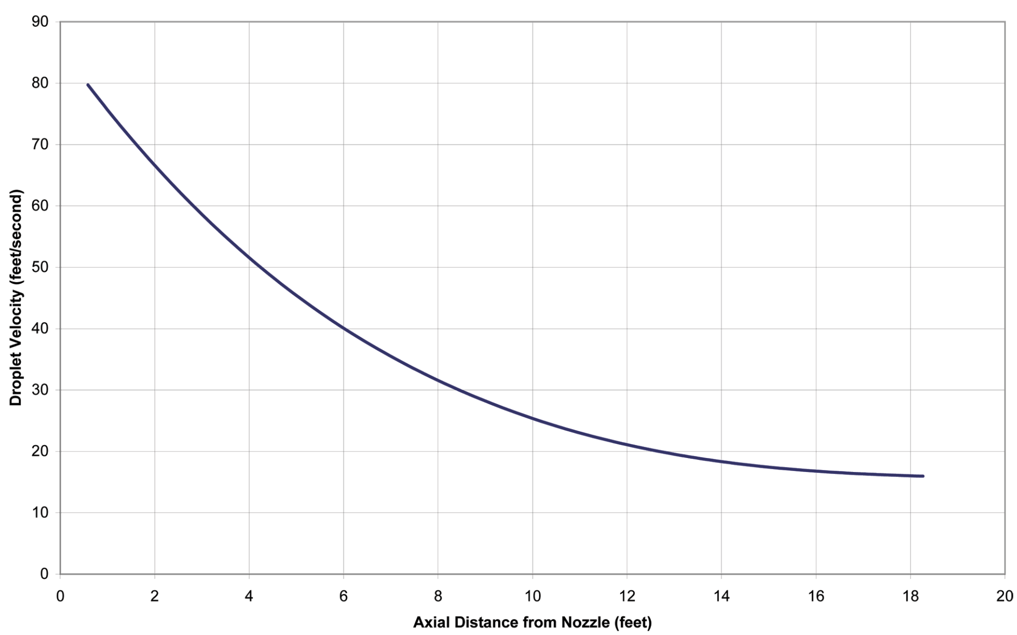
Droplet Velocity for the TF40FCN Spraying Vertically Down at 40 PSI and DV0.9 = 1380 Microns



TF 40 FCN

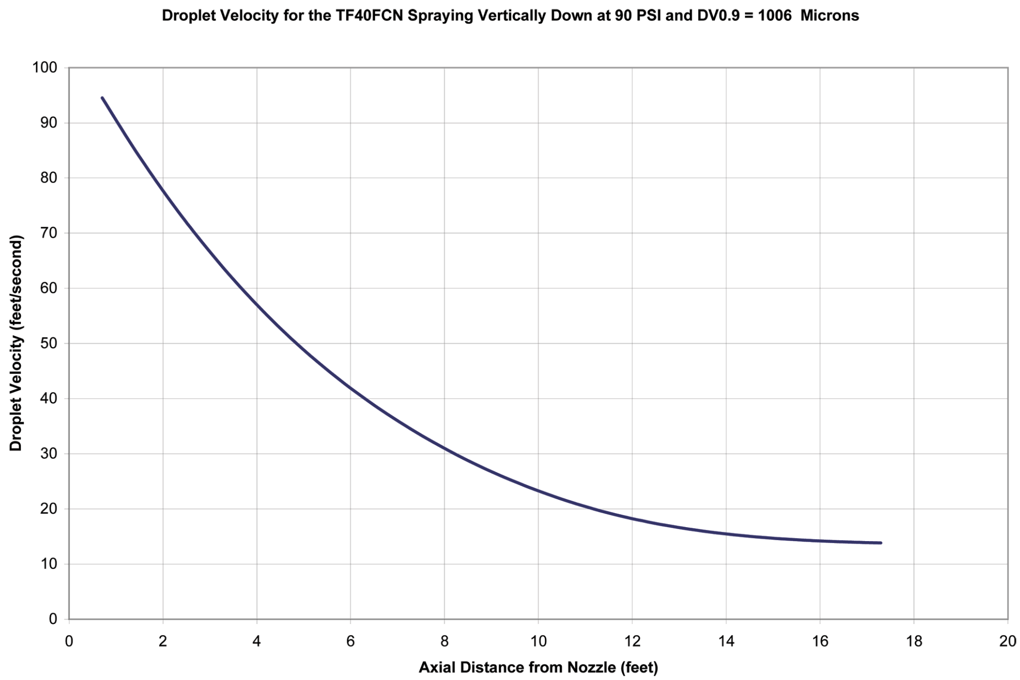
Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter

Droplet Velocity for the TF40FCN Spraying Vertically Down at 60 PSI and DV0.9 = 1179 Microns



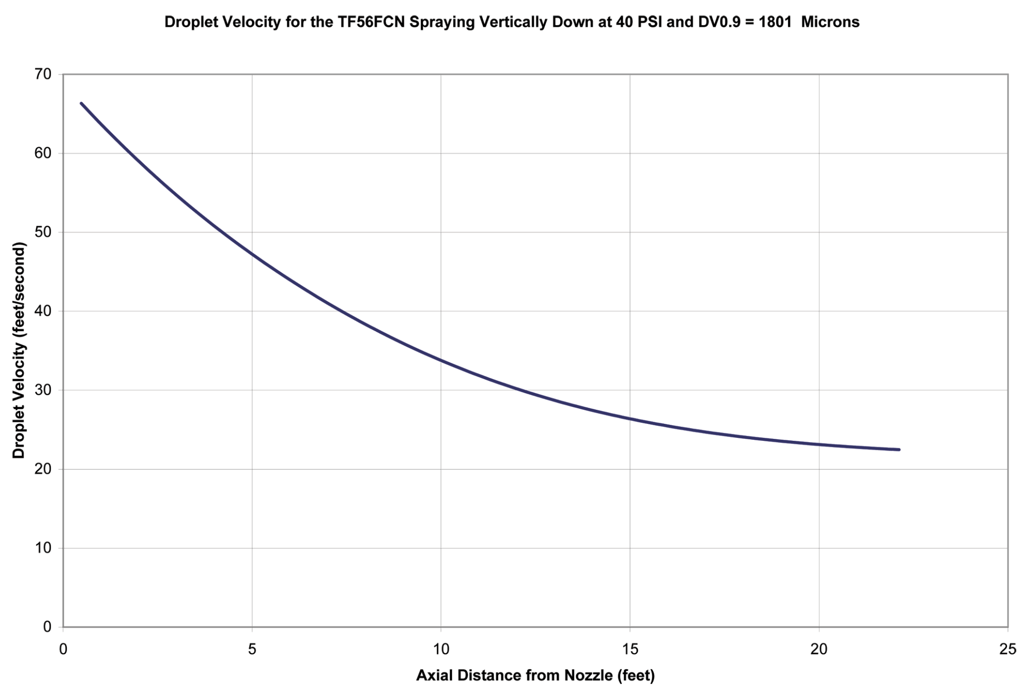
TF 40 FCN

Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter



TF 40 FCN

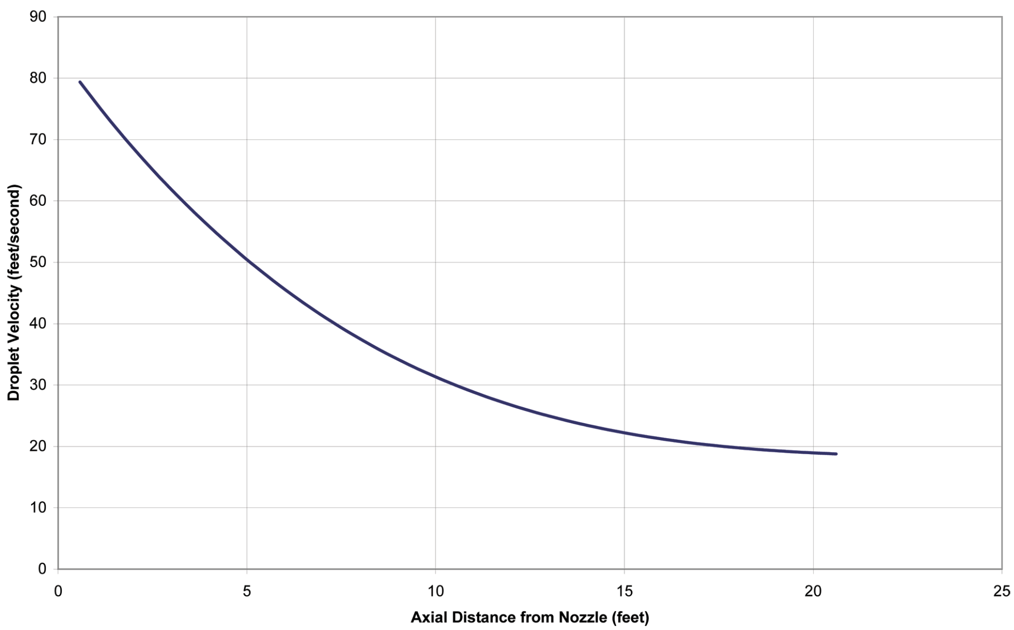
Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter



TF 56 FCN

Droplet Velocity. Spraying Vertically Downward at 40 psi. DV0.9 Droplet Diameter

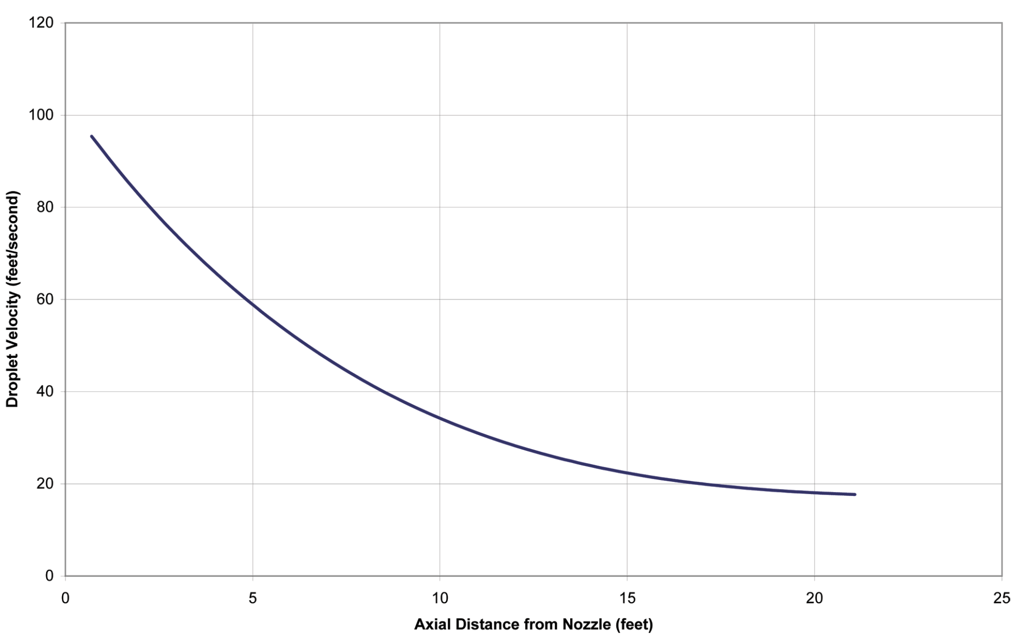
Droplet Velocity for the TF56FCN Spraying Vertically Down at 60 PSI and DV0.9 = 1411 Microns



TF 56 FCN

Droplet Velocity. Spraying Vertically Downward at 60 psi. DV0.9 Droplet Diameter

Droplet Velocity for the TF56FCN Spraying Vertically Down at 90 PSI and DV0.9 = 1312 Microns



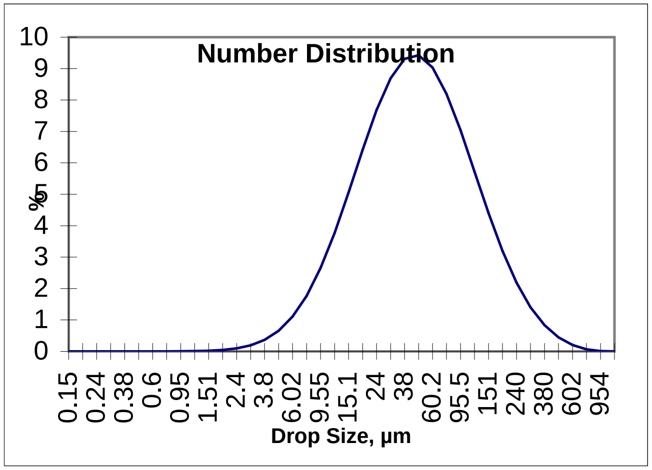
TF 56 FCN

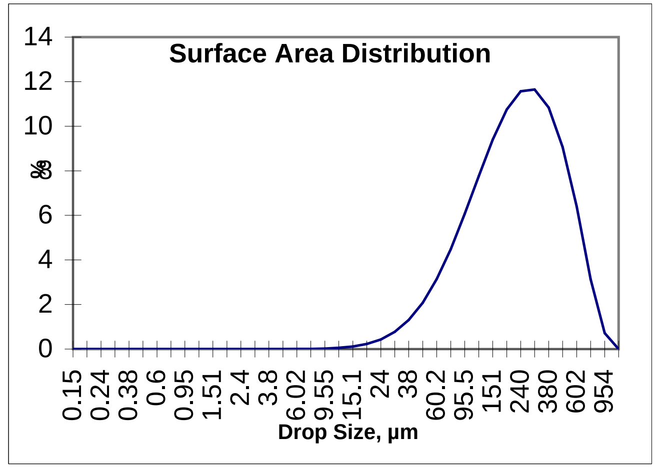
Droplet Velocity. Spraying Vertically Downward at 90 psi. DV0.9 Droplet Diameter

Appendix B

Droplet Size Distribution Curves
Technical Data

TF16FCN at 40 psi





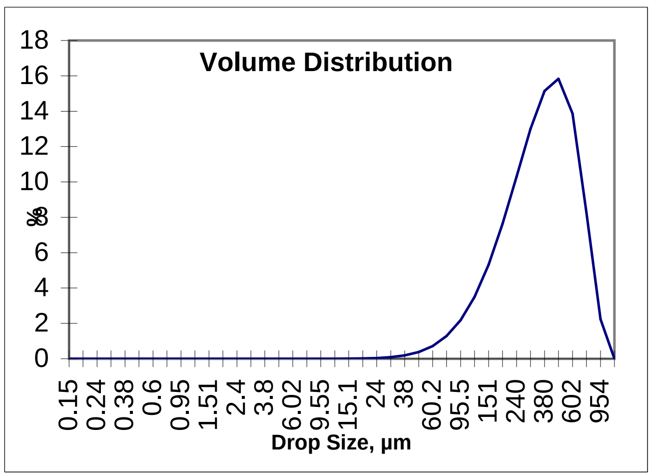
sg= 1

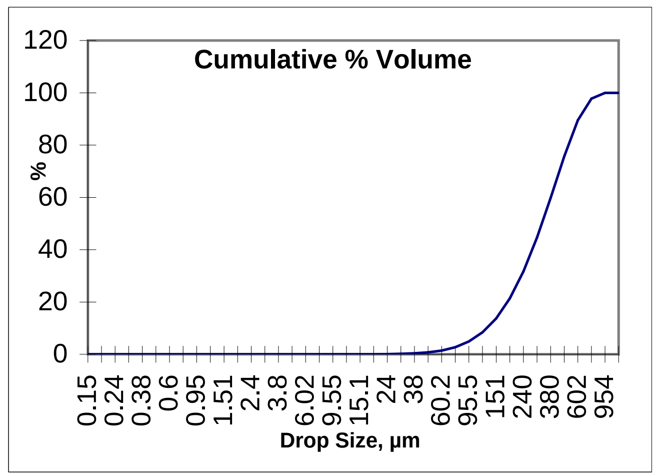
1 cp

10.6 gpm

D32=280

DV0.5=370

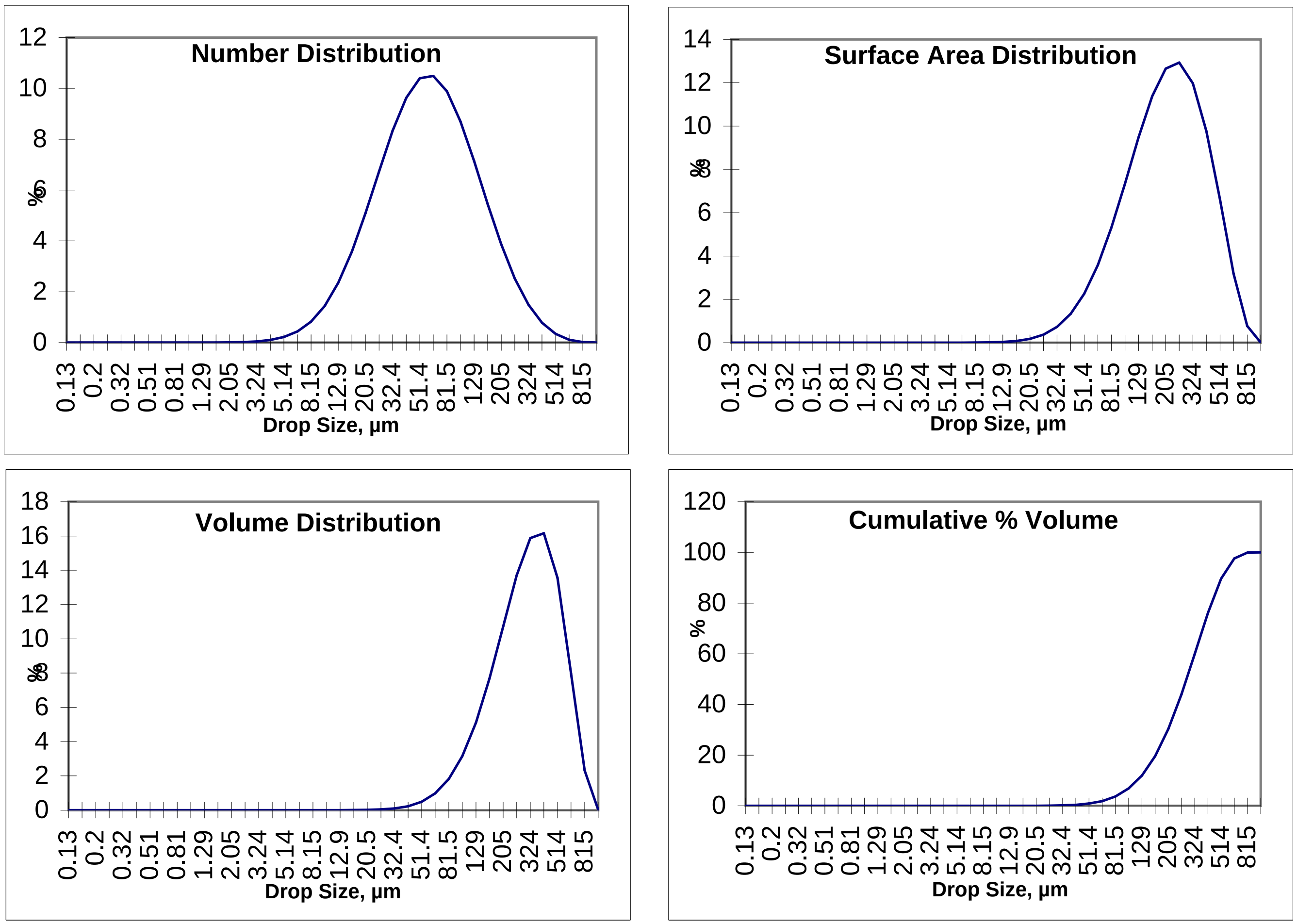




Note:Droplet Sizes are in Microns

source: automatic

TF16FCN at 60 psi

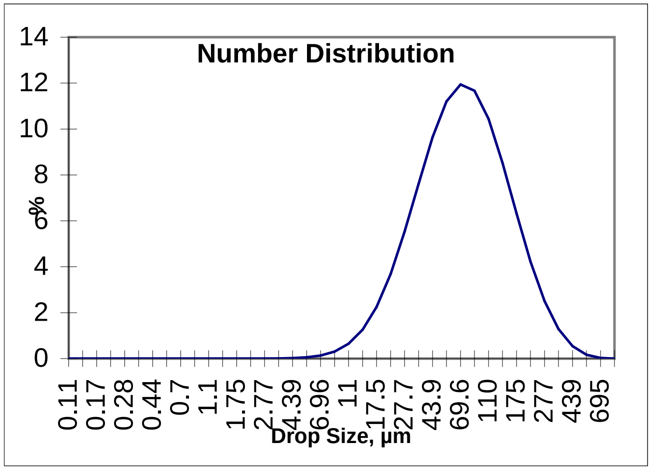


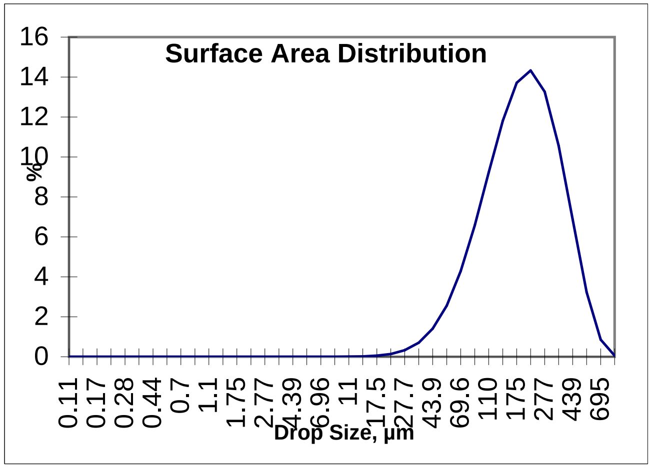
sg= 1
1 cp
13 gpm
D32=250
DV0.5=310

Note:Droplet Sizes are in Microns

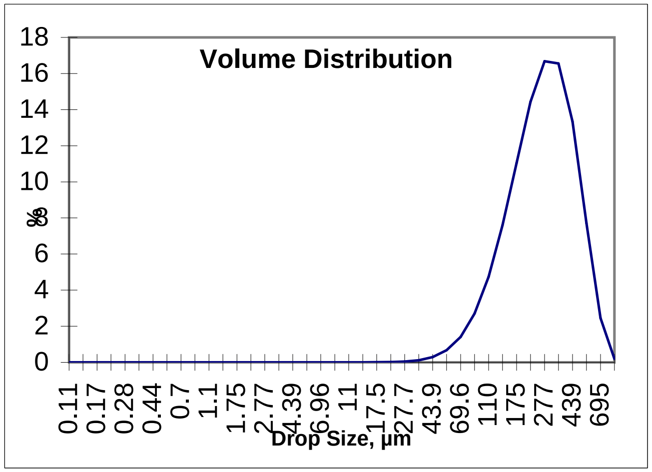
source: automatic

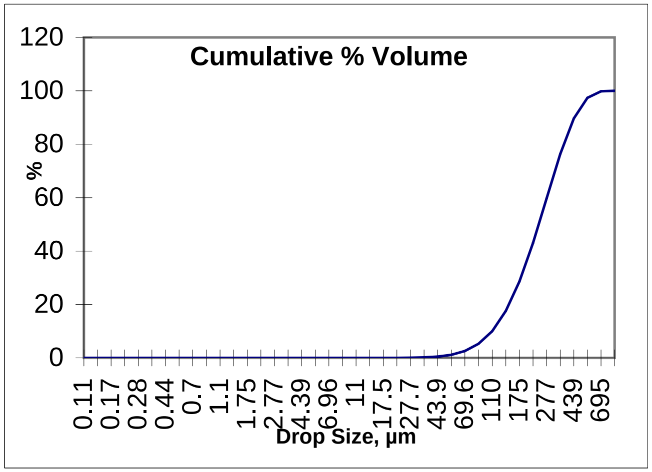
TF16FCN at 90 psi





sg= 1
1 cp
15.9 gpm
D32=220
DV0.5=270





Note:Droplet Sizes are in Microns

source: automatic

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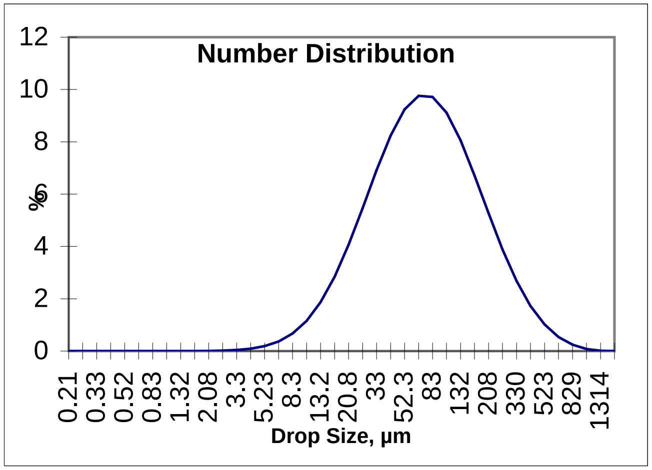
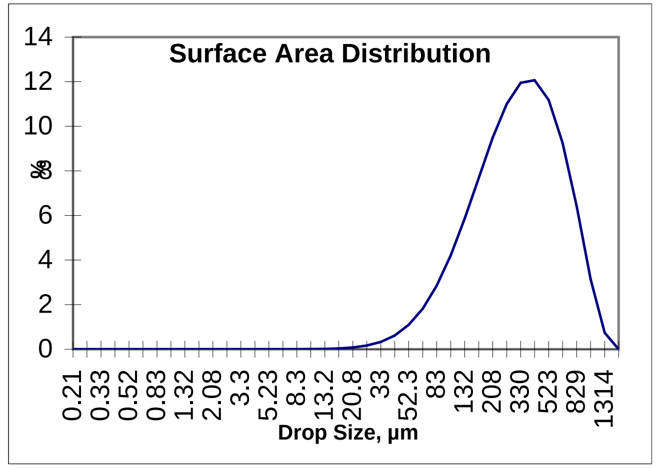
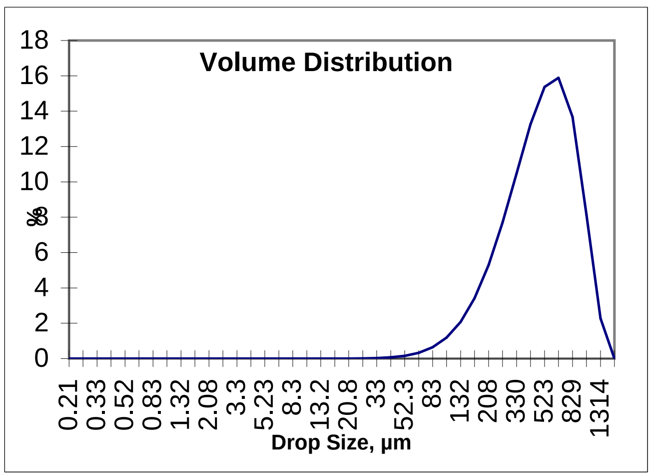
Applications Engineering Department
Estimated Drop Size Information

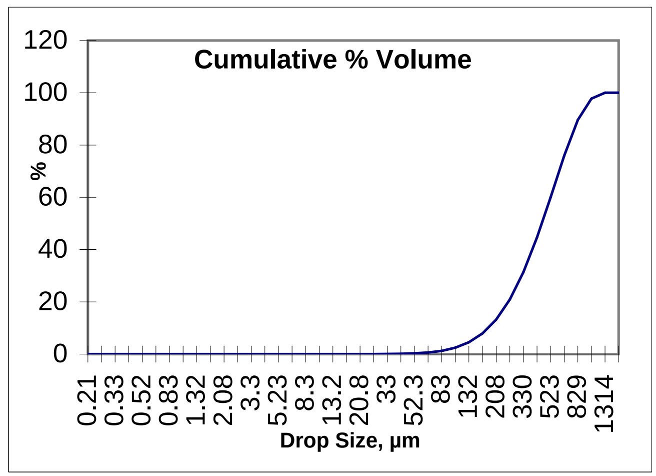
TF24FCN at 40 psi





sg= 1
1 cp
24.1 gpm
D32=380
DV0.5=500

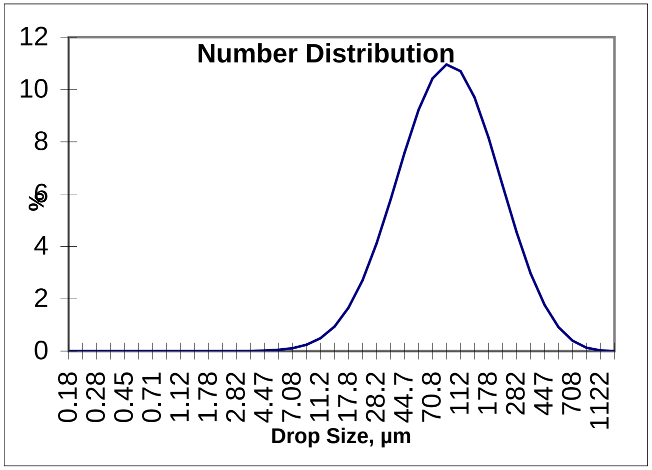


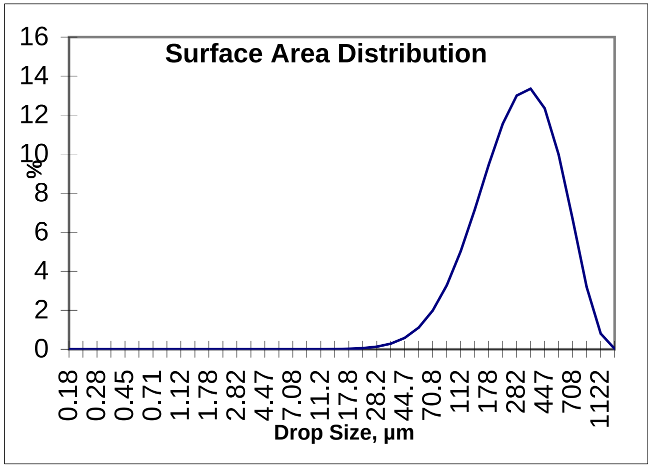


Note:Droplet Sizes are in Microns

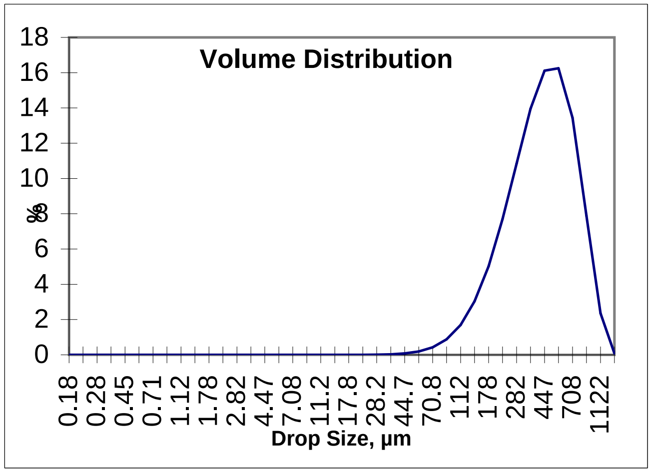
source: automatic

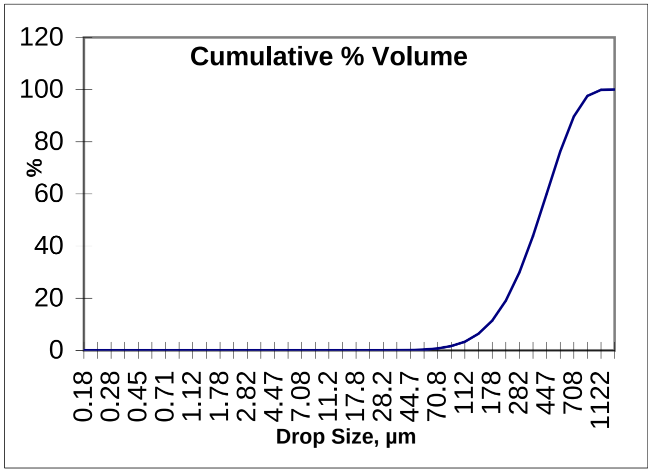
TF24FCN at 60 psi





sg= 1
1 cp
29.5 gpm
D32=340
DV0.5=430

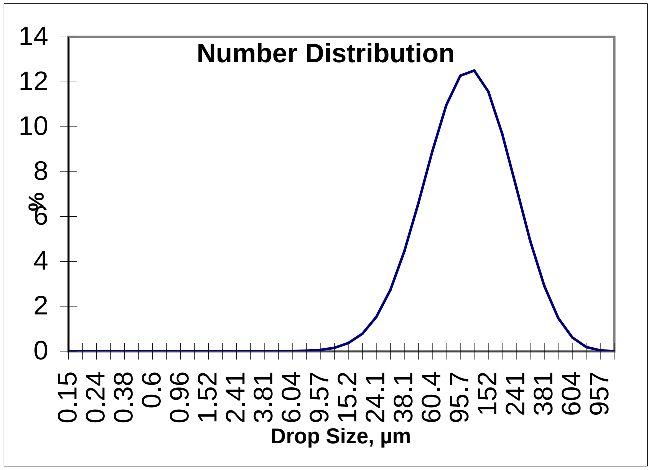


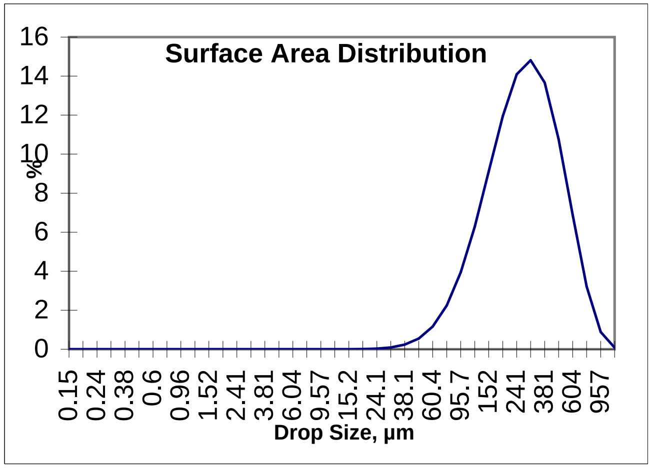


Note:Droplet Sizes are in Microns

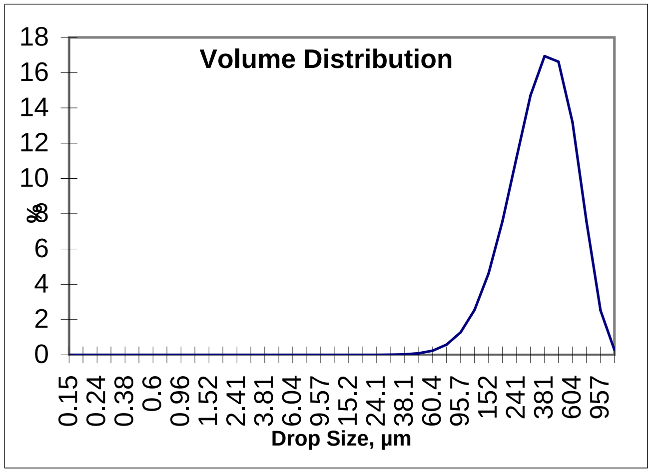
source: automatic

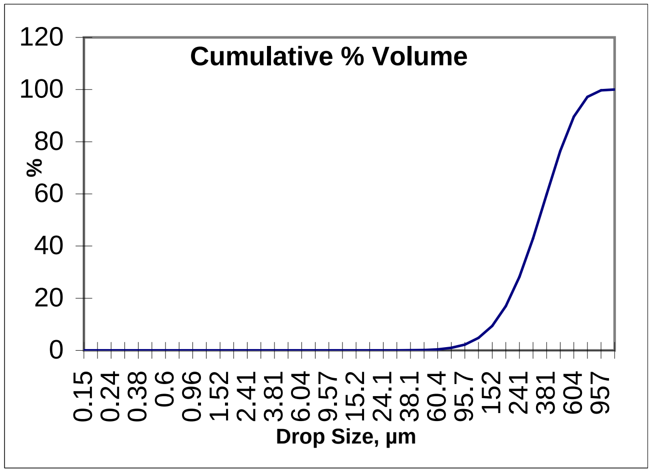
TF24FCN at 90 psi





sg= 1
1 cp
36.1 gpm
D32=300
DV0.5=370

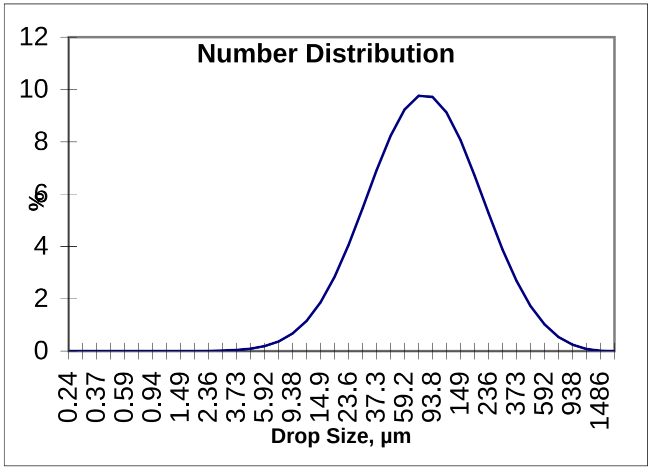


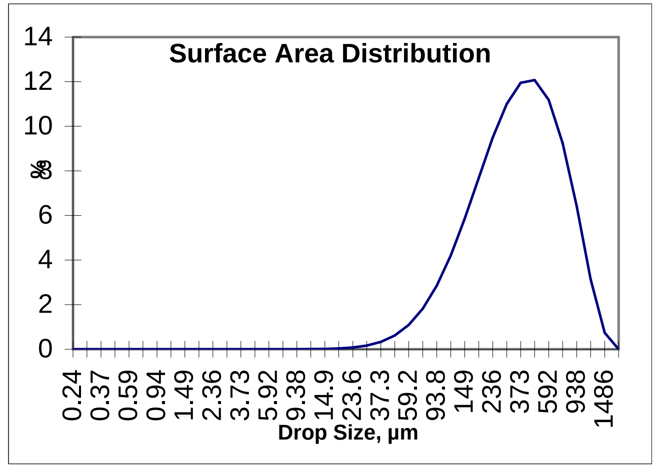


Note:Droplet Sizes are in Microns

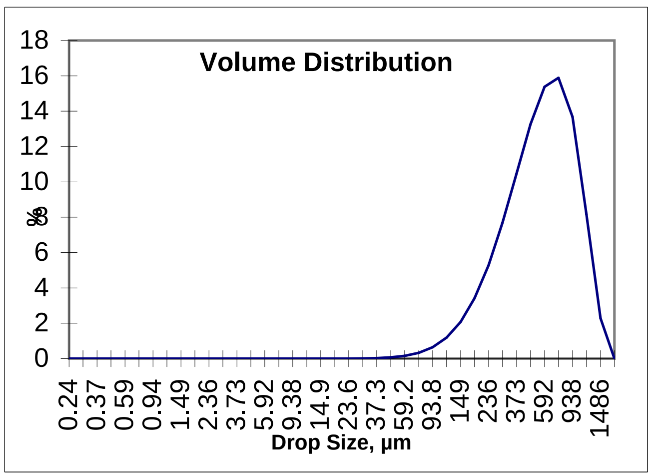
source: automatic

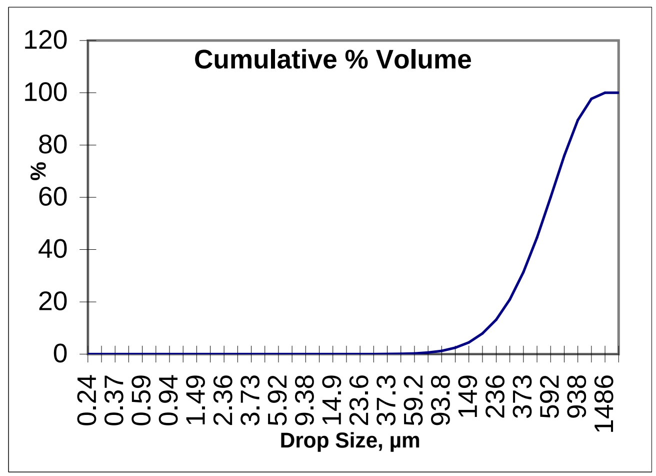
TF28FCN at 40 psi





sg= 1
1 cp
33 gpm
D32=430
DV0.5=570

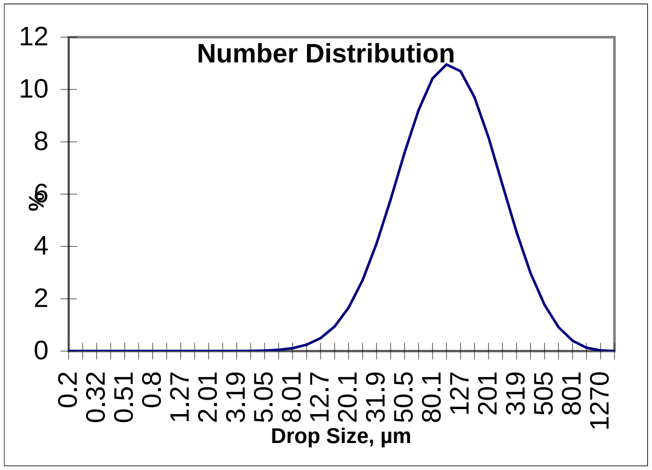


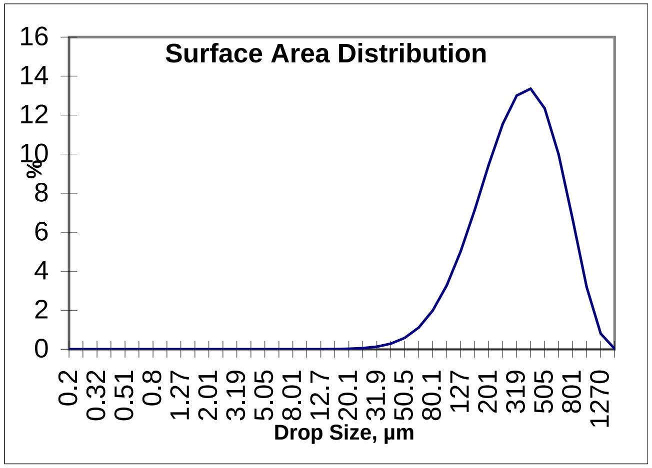


Note:Droplet Sizes are in Microns

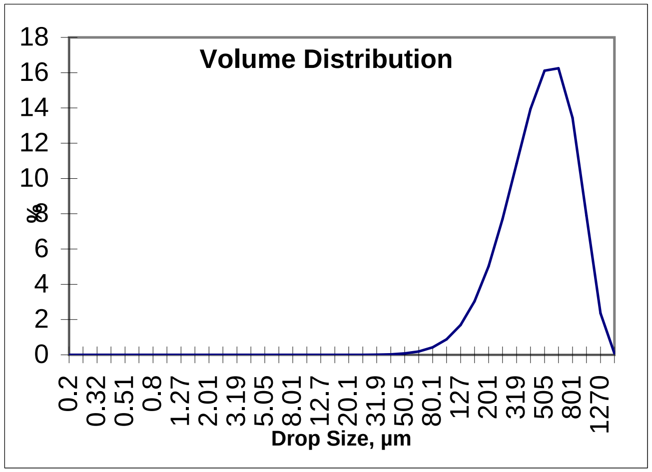
source: automatic

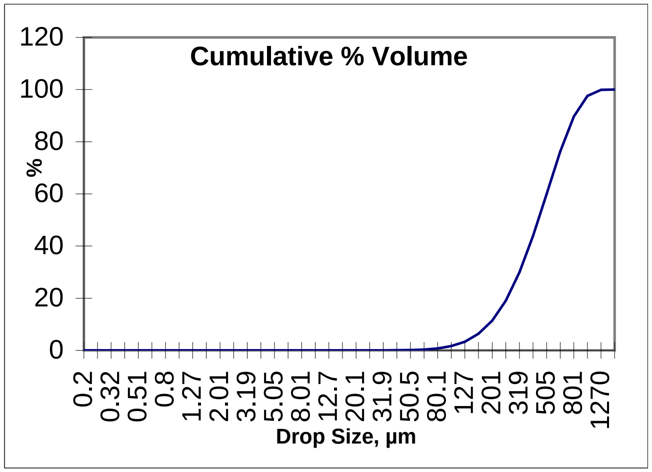
TF28FCN at 60 psi





sg= 1
1 cp
40.4 gpm
D32=380
DV0.5=490



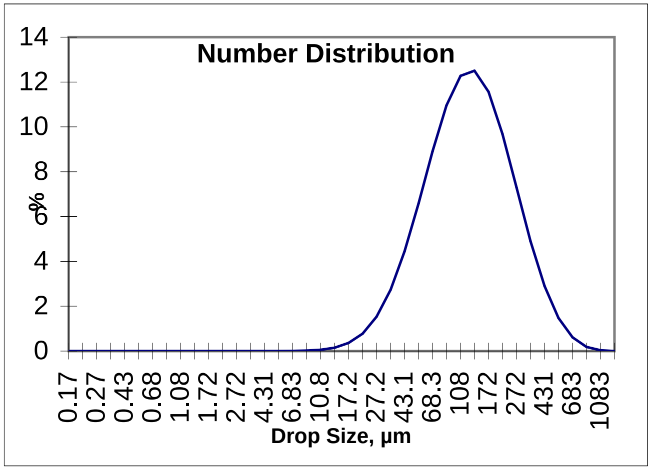


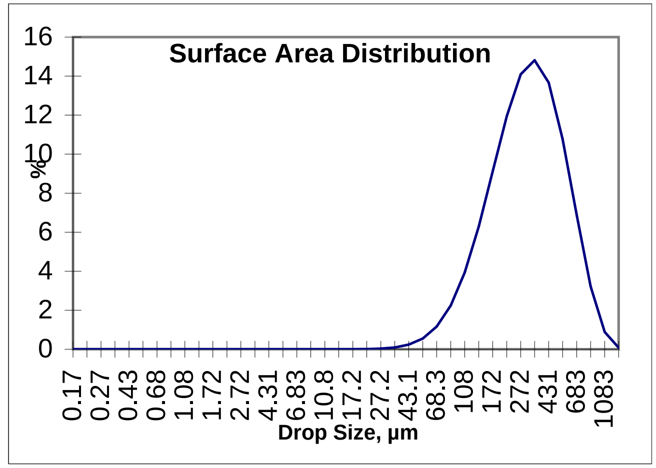
Note:Droplet Sizes are in Microns

source: automatic

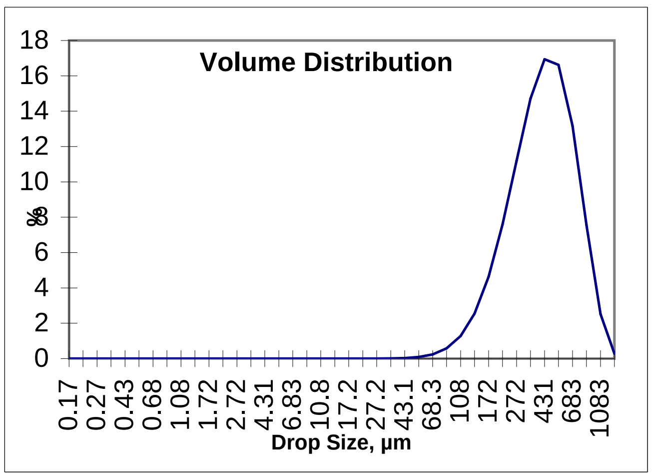
Applications Engineering Department
Estimated Drop Size Information

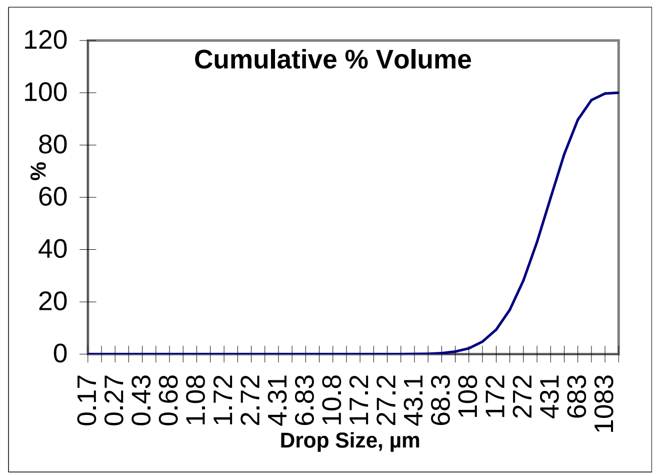
TF28FCN at 90 psi





sg= 1
1 cp
49.5 gpm
D32=340
DV0.5=420



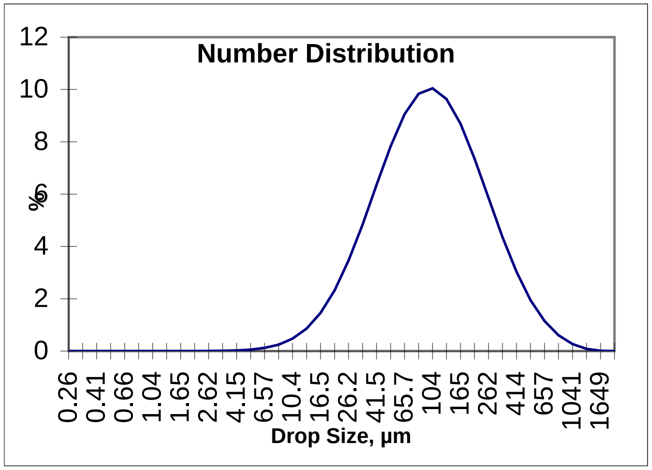


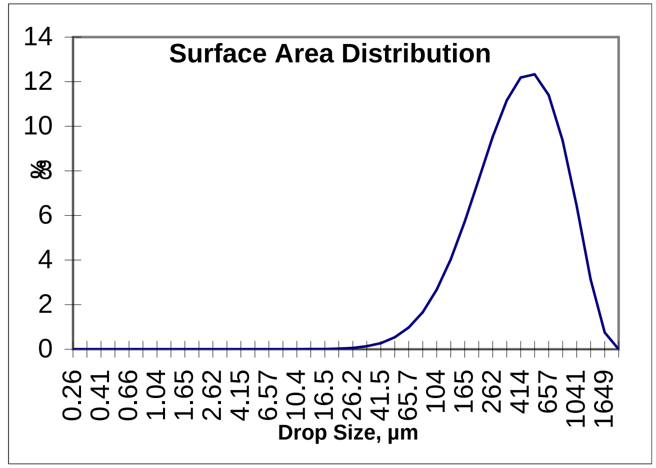
Note:Droplet Sizes are in Microns

source: automatic

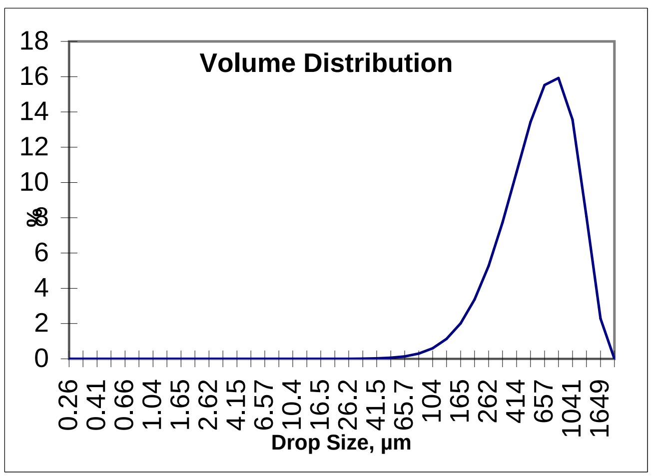
Applications Engineering Department
Estimated Drop Size Information

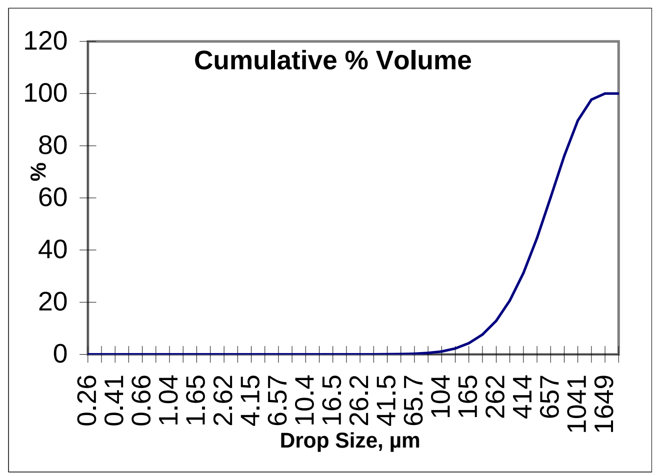
TF32FCN at 40 psi





sg= 1
1 cp
42 gpm
D32=480
DV0.5=630



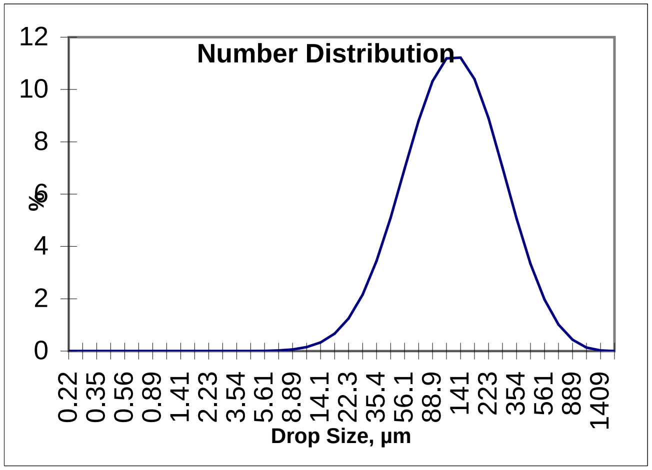


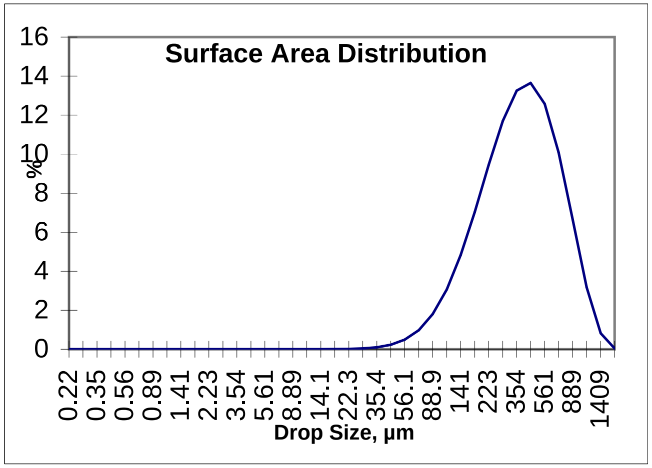
Note:Droplet Sizes are in Microns

source: automatic

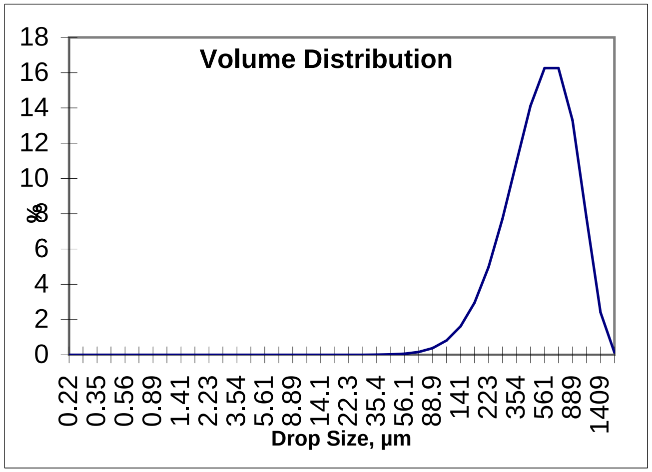
Applications Engineering Department
Estimated Drop Size Information

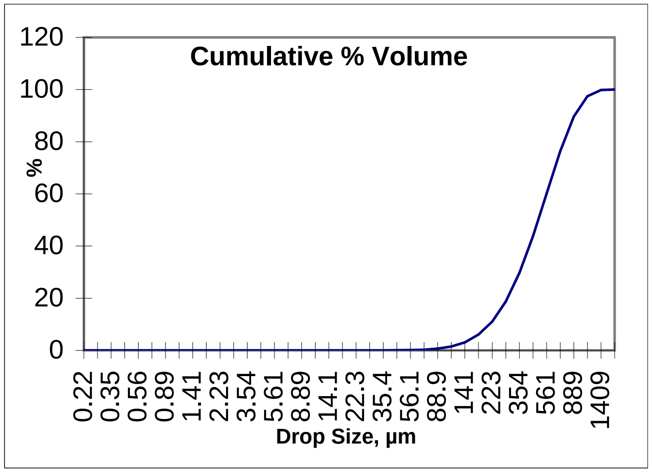
TF32FCN at 60 psi





sg= 1
1 cp
51.4 gpm
D32=420
DV0.5=540





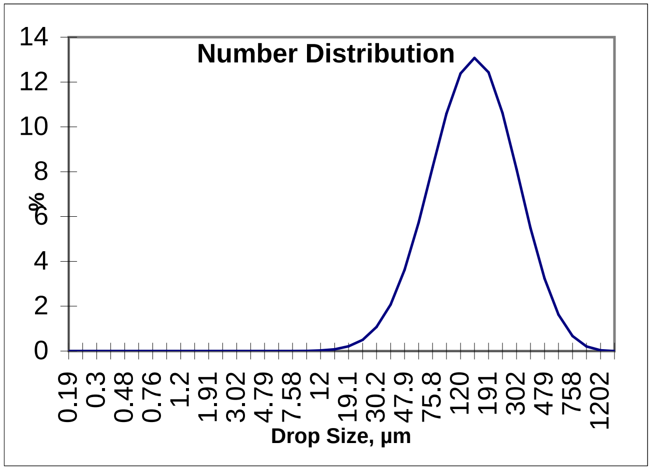
Note:Droplet Sizes are in Microns

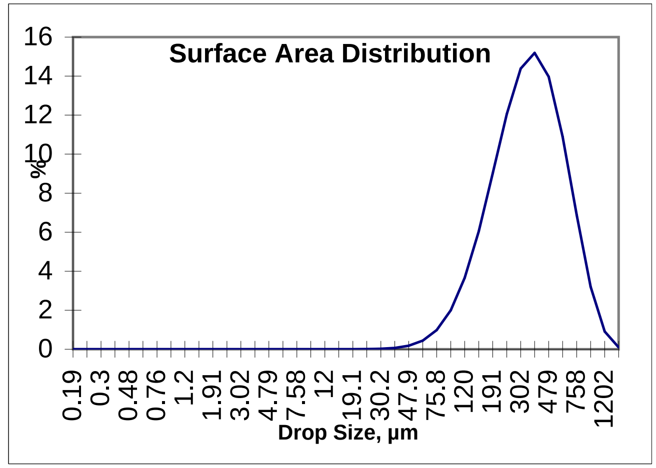
source: automatic

BETE

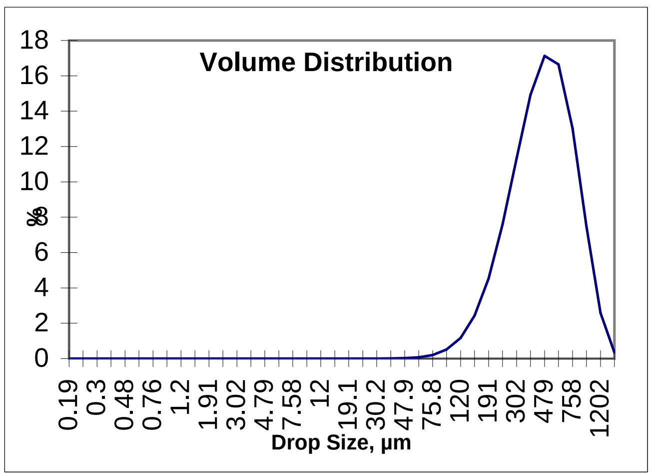
Applications Engineering Department
Estimated Drop Size Information

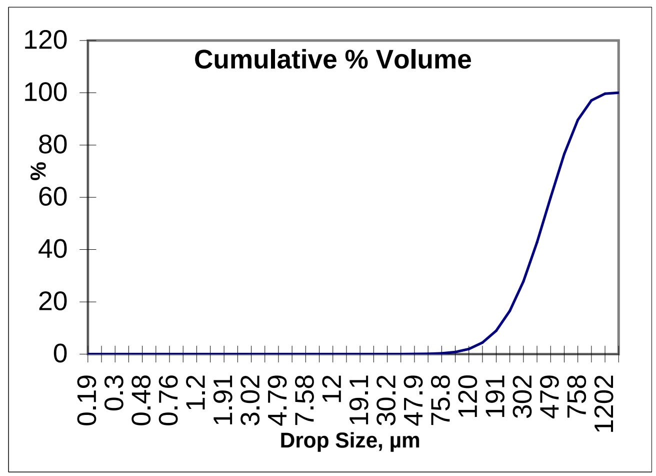
TF32FCN at 90 psi





sg= 1
1 cp
63 gpm
D32=380
DV0.5=470

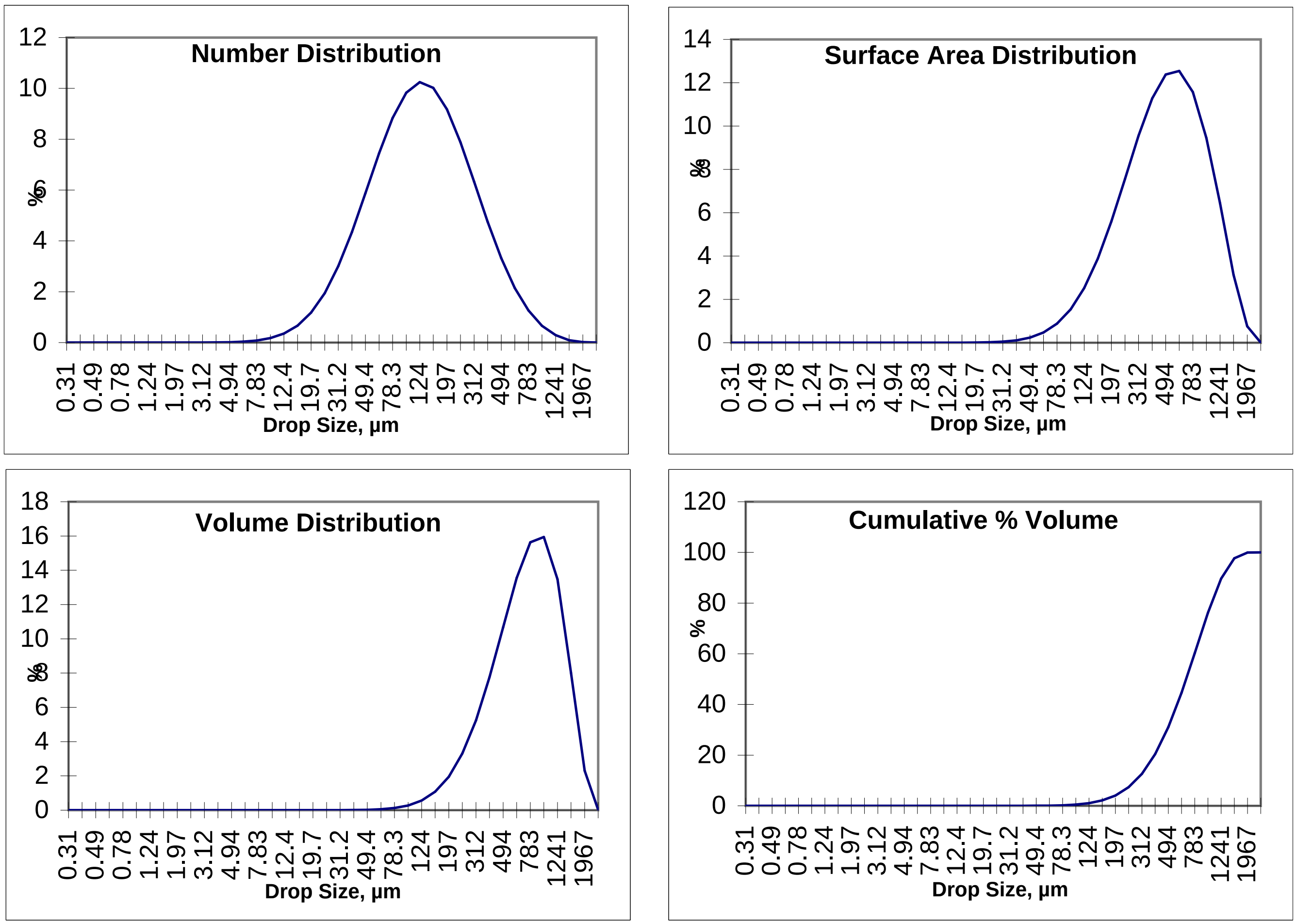




Note:Droplet Sizes are in Microns

source: automatic

TF40FCN at 40 psi



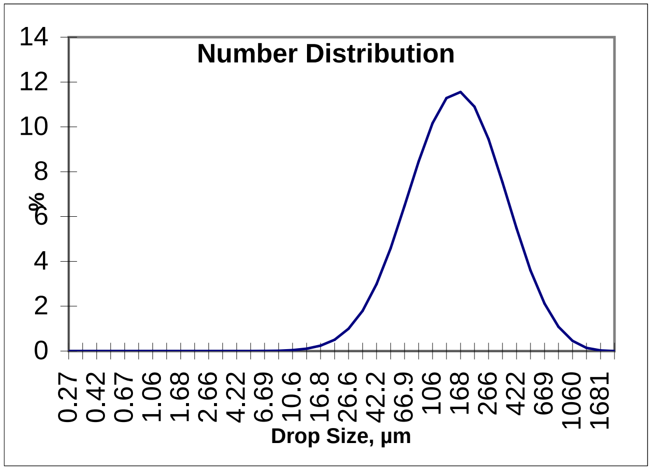
sg= 1
1 cp
67 gpm
D32=570
DV0.5=750

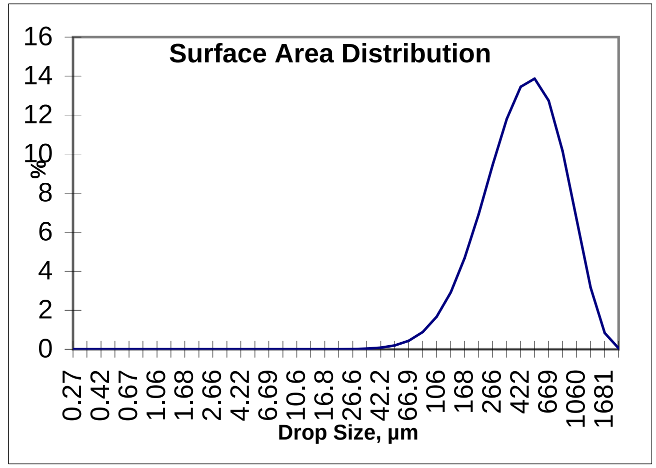
Note:Droplet Sizes are in Microns

source: automatic

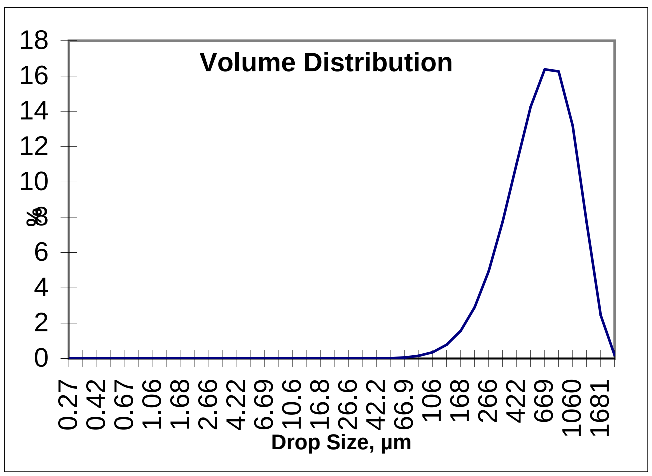
Applications Engineering Department
Estimated Drop Size Information

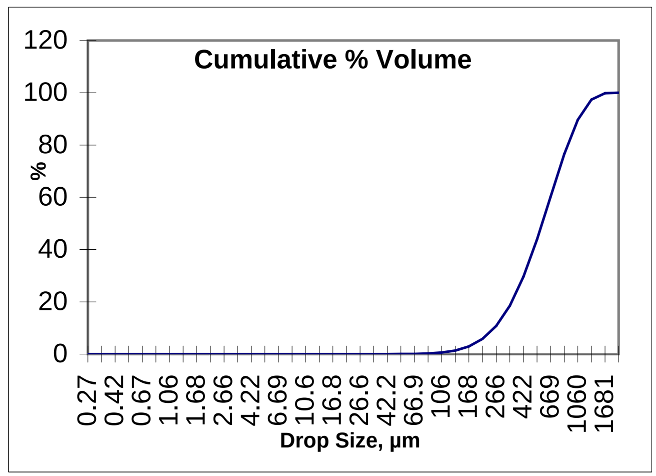
TF40FCN at 60 psi





sg= 1
1 cp
82.1 gpm
D32=510
DV0.5=650

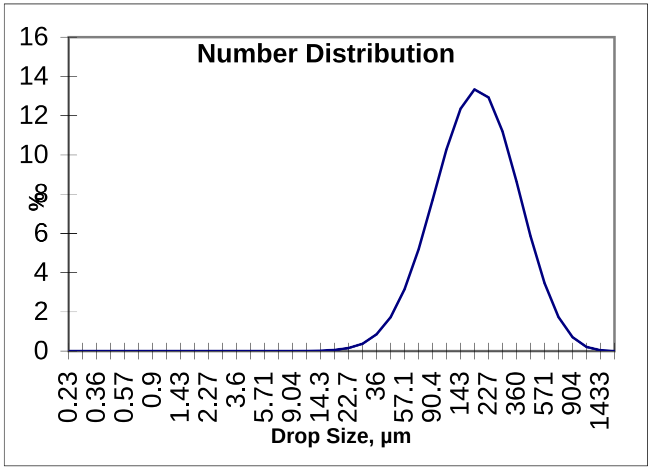


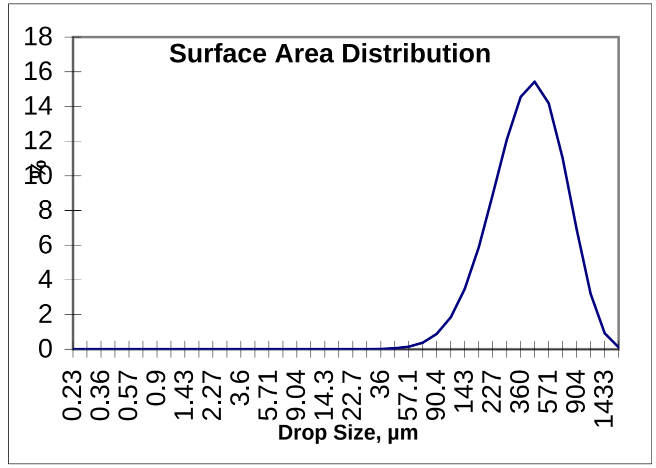


Note:Droplet Sizes are in Microns

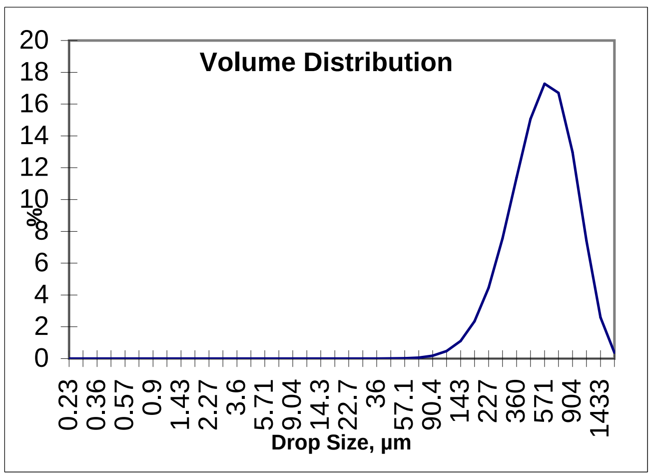
source: automatic

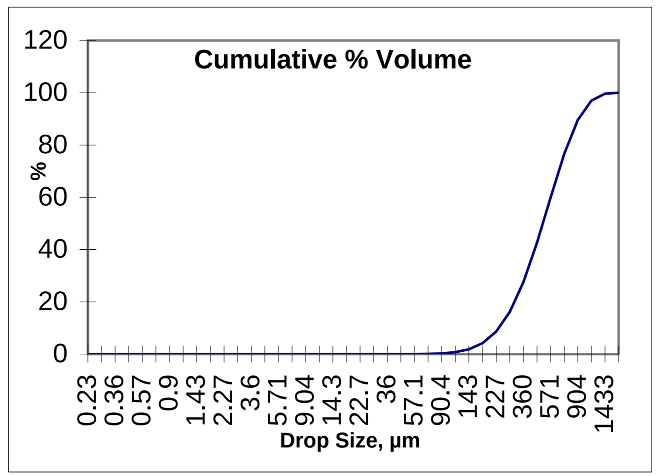
TF40FCN at 90 psi





sg= 1
1 cp
101 gpm
D32=450
DV0.5=560

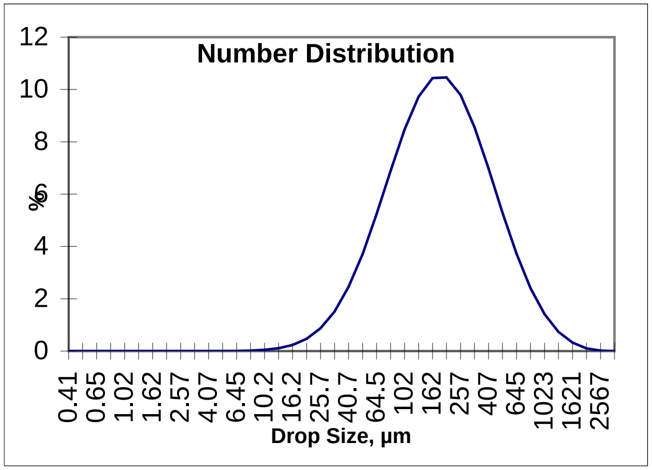


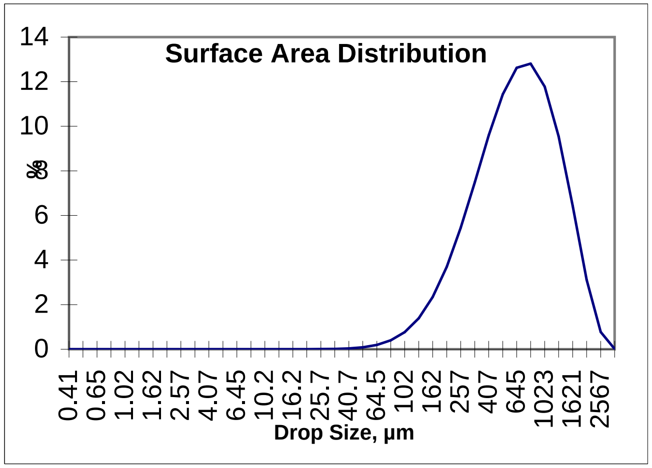


Note:Droplet Sizes are in Microns

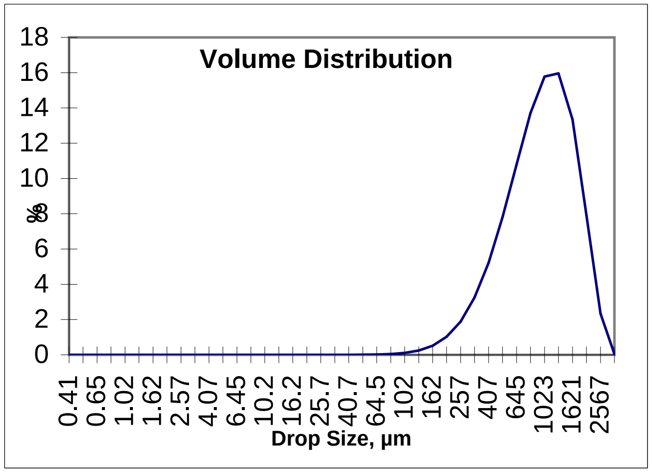
source: automatic

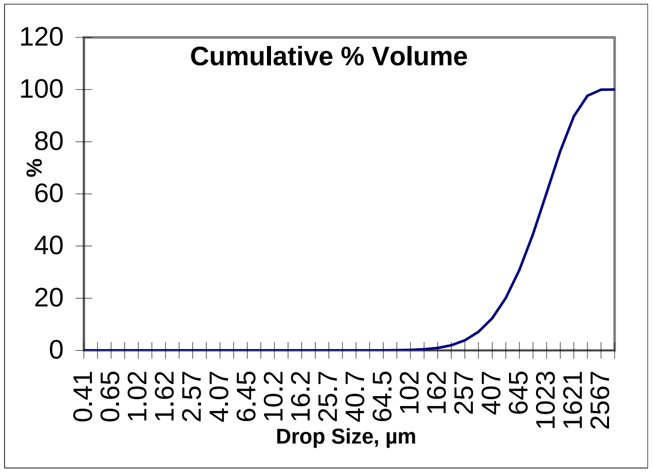
TF56FCN at 40 psi





sg= 1
1 cp
129 gpm
D32=750
DV0.5=980

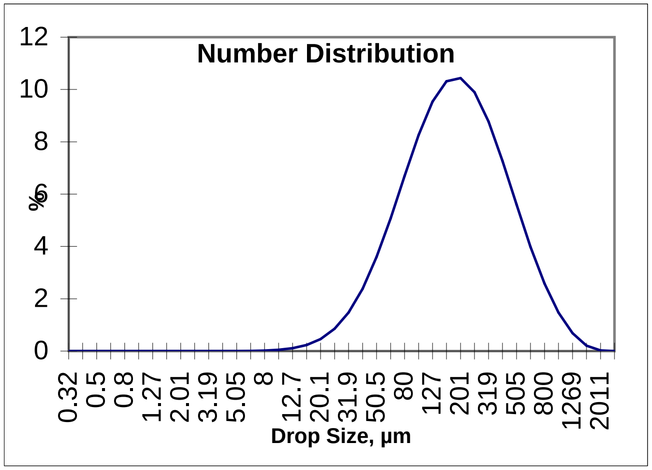


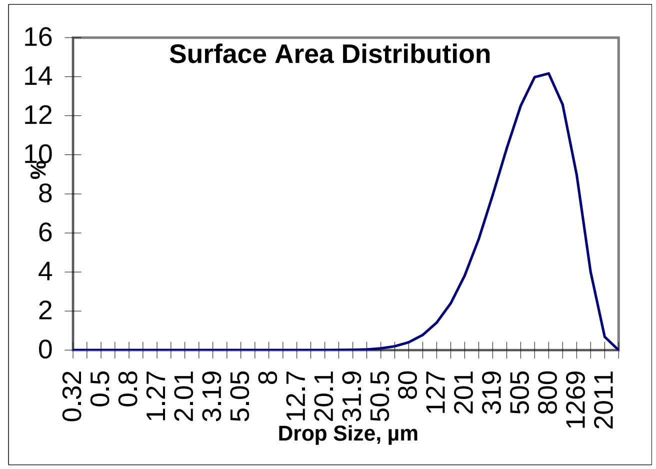


Note:Droplet Sizes are in Microns

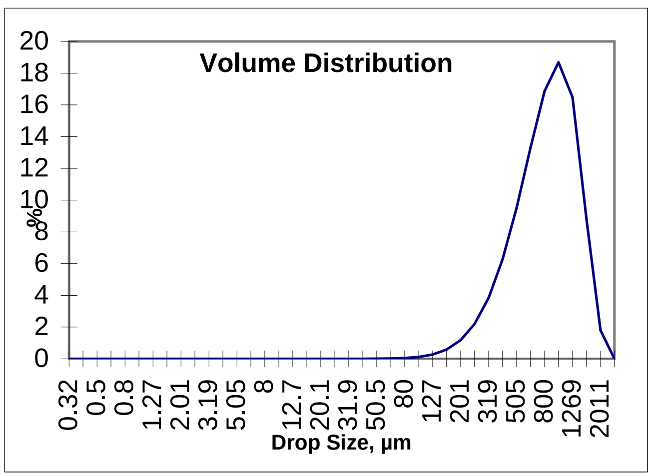
source: automatic

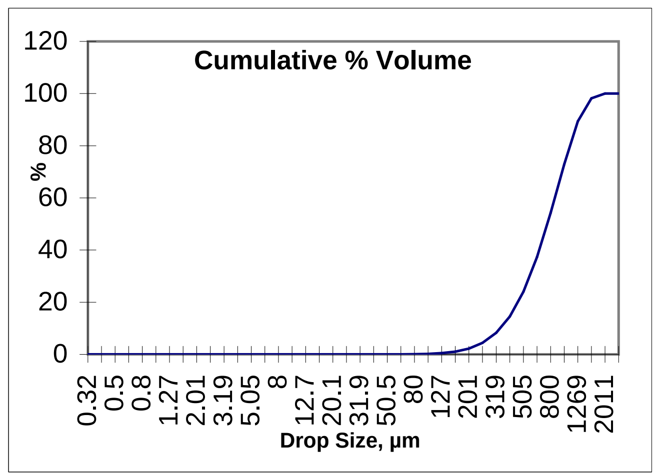
TF56FCN at 60 psi





sg= 1
1 cp
158 gpm
D32=660
DV0.5=850

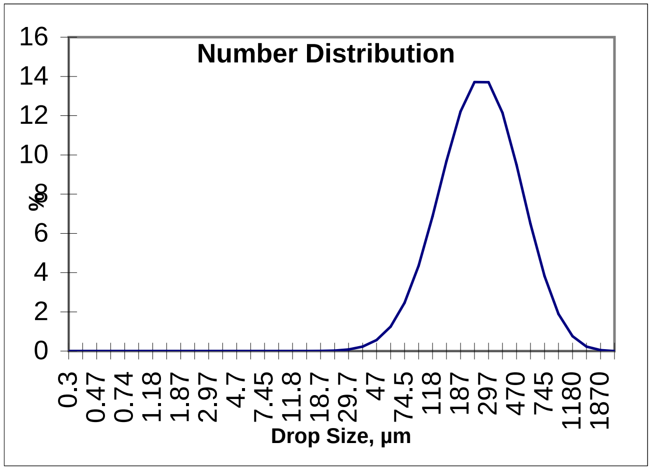


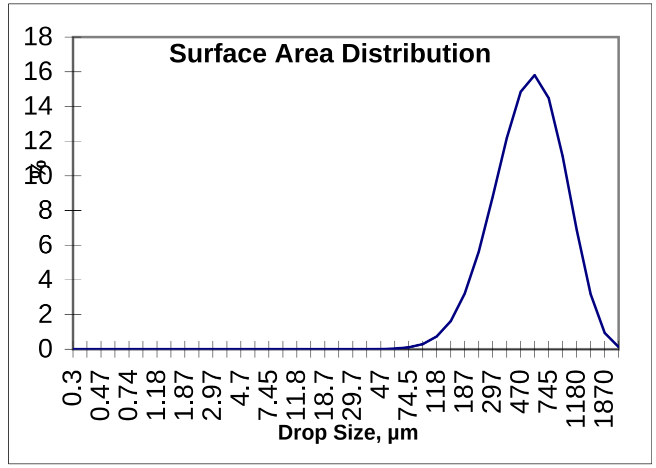


Note:Droplet Sizes are in Microns

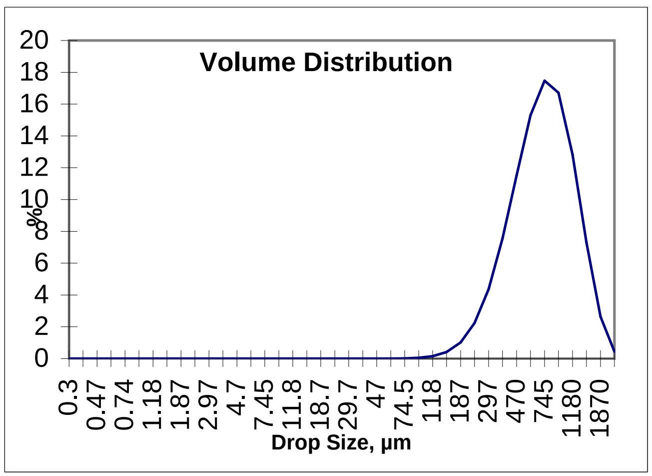
source: automatic

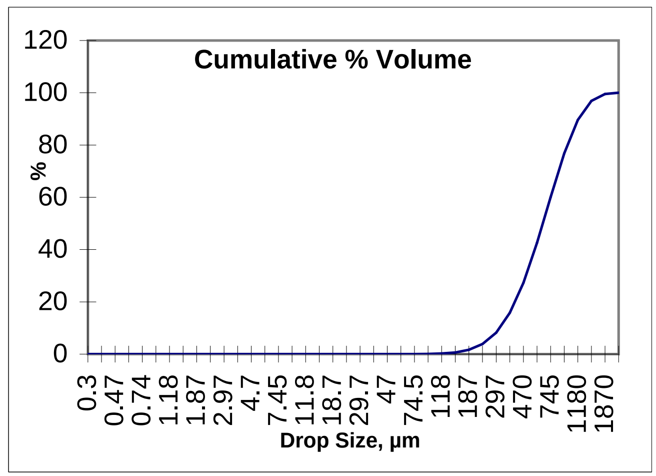
TF56FCN at 90 psi





sg= 1
1 cp
194 gpm
D32=590
DV0.5=730





Note:Droplet Sizes are in Microns

source: automatic