

Predicting the Microgravity Performance of Terrestrial Portable Fire Extinguishers

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Portable fire extinguishers (PFEs) are a key component of spacecraft emergency response systems. The International Space Station uses custom PFEs to meet the unique microgravity and enclosed space requirements of the vehicle. For future crewed missions to Low Earth Orbit and Deep Space destinations, terrestrial commercial off-the-shelf (COTS) PFEs may offer more economical solutions for the destination as well as the visiting vehicle. However, depending on the design of both the spacecraft and the PFE, the reduced gravity environment is likely to impact PFE performance, especially when multiphase microgravity liquid transport processes are present. Additionally, many terrestrial PFEs now use halocarbons as the suppressant. While studies show these are effective in certain terrestrial fires, some data suggest that low concentrations may actually exacerbate a fire, a phenomenon that would prove particularly concerning in spacecraft. To better characterize the potential of employing COTS hardware, two terrestrial PFEs, one charged with HFC-227ea and Nitrogen pressurant and one charged with carbon dioxide, were modeled to predict performance in both 1-g and microgravity environments. Testing was conducted in 1-g to validate the model. Testing was also conducted to evaluate the effect of sub-extinguishment HFC-227ea concentrations on burn rate in controlled samples. Here we provide a detailed description of the model, report the methods and results of PFE testing, discuss the predicted effects of microgravity on PFE performance, and report the results of material burn rates at sub-extinguishment levels of HFC-227ea.

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Nomenclature

A	=	PFT tank section area	A_c	=	effective tube/valve/nozzle area
Bo	=	Bond number, $\equiv \rho g R^2 / \sigma$	c_d	=	PFE discharge coefficient
C_D	=	flow resistance coefficient	ϕ	=	PFE tank liquid fill fraction
g, g_o	=	acceleration, 9.8 m/s^2	γ	=	ratio of specific heats
h	=	height of meniscus in PFE	H	=	effective height of PFE
L	=	length of liquid along exit tube	$\dot{m}$	=	mass flow rate
m	=	mass of fluid	μ	=	dynamic viscosity
PFE	=	Portable Fire Extinguisher	P	=	PFE tank pressure
θ	=	contact angle	R	=	PFE tank radius and gas constant
RSU	=	Right-side-up	ρ	=	density
σ	=	surface tension	t	=	time
T	=	Tank Temperature	U	=	Exit velocity
USD	=	Up-side-down	V	=	PFE tank volume
We	=	Weber number $\equiv \rho U^2 R / \sigma$	x	=	gas/vapor quality

I. Introduction and Contents

Fire in any enclosed environment represents a time-critical safety emergency. Protecting humans from this risk is particularly challenging in spacecraft, where micro- or partial gravity, constrained access to confined spaces, limited mass and volume allocations for emergency response hardware, and proximity to safe-haven or emergency return vehicles limit crew options for fire response. The most fundamental line of defense, once a fire is initiated, is arguably portable fire extinguishers (PFE), which allow a crew member to directly respond to an active fire. Requirements for PFE's depend on the application. The main factors that influence the design of the fire suppression system include accessibility of the fire protection location, presence of forced air flow, credible O₂ enrichment scenarios, and potential ignition sources.

The ISS program has very basic fire suppression requirements for the ISS itself, described in SSP 41000 and 50021 (later superseded by SSP 51721).¹⁻³ Certain situations are outlined that require fixed fire suppression (though the ISS has no fixed fire suppression system), but a crew operable PFE is always required. The type of suppressant is specified as carbon dioxide (CO₂) only, although water mist PFEs were added in late 2015 and early 2016.⁴ In both fixed and portable cases, there is a performance requirement that says the oxygen concentration at the fire event location must be less than 10.5% within one minute of suppressant discharge and that it does not raise the partial pressure of CO₂ in the open cabin above 34.2 mmHg. There is an additional requirement that fixed systems must complete application of fire suppressant within one minute of initiation. Both requirements are intended to be verified by analysis using qualification data.

The ISS program expanded fire suppression requirements for crewed visiting vehicles⁵⁻⁶ to provide flexibility so that efficient solutions can be tailored to vehicle design characteristics. The main factors in fire suppression system design identified above for ISS are the same for visiting vehicles. A guide is used to inform the fire suppression design and a crew operable PFE is required. The capacity of the PFE and type of suppressant are not specified for visiting vehicles, but performance characteristics based on two categories of suppressant types are provided. The first category consists of PFEs using CO₂ as a suppressant and leverages two main performance criteria (the same as for the ISS itself), which are that O₂ concentration must be reduced below 10.5% within one minute at the fire event location and that release of CO₂ will not raise the CO₂ concentration in the open cabin above 34.2 mmHg. The second category consists of PFEs using any type of suppressant other than CO₂. Termed 'alternative' suppressants, the related requirements focus primarily on compatibility with ISS systems and crew safety, with only one performance criteria which is that fires must be extinguished within one minute of application. Verification of CO₂ PFE performance is specified as volumetric analysis using PFE qualification data, while verification of alternative suppressants specifies both analysis and demonstration. Specific demonstration criteria are not provided except for a high-level objective that states "...that the alternative fire suppressant can extinguish a fire within one minute of application." In some circumstances a fixed fire suppression system is also required, which has the same performance criteria as the CO₂ PFE requirement but does not limit the suppressant choice to CO₂. For example, other O₂ displacement suppressants such as nitrogen could be allowed if they meet the 10.5% requirement. Fixed fire suppression also has a requirement that application of fire suppressant must be complete within 1 minute of initiation. Verification of fixed fire suppression systems is specified as volumetric analysis using qualification data.

Notably absent from any of these requirements or verifications is direction for how to treat 2-phase suppressants, adjusting for microgravity considerations, and specific guidance related to suppressant usage such as dwell time at the fire location, specific types and sizes of fires, and specific standardized tests or certifications. Additionally,

qualification data, especially for COTS PFEs, would typically leverage manufacturer specifications and testing which is likely based on 1-g performance data and/or terrestrial standardized tests to demonstrate effectiveness. Given the complexity and cost of custom PFEs for spacecraft, this is particularly relevant for future vehicles developed by commercial entities that may consider commercial-off-the-shelf (COTS) PFE options used commonly for terrestrial applications. Direct application of these terrestrial PFEs may come at the cost of reduced performance due to reduced gravity and close, confined living spaces, avionics compartments, and science and experiment fixtures.

It has been long established that static and dynamic fluid phenomena are significantly impacted by the near weightless environment of orbiting or coasting spacecraft. Large pressurized partially-liquid-filled portable or fixed fire extinguishers are no exception (i.e., water, HFC-227ea, CO₂, Novec 1230, etc.). Terrestrial PFEs of this sort often employ a siphon tube that efficiently accesses and drains the active liquid contents, because the liquid pools at the base of the ‘upright’ PFE due to gravity as illustrated in Figure 1a. Unfortunately, this passive mechanism is not available in microgravity environments. To establish a measure of quantitative expectations, we provide herein a summary of analyses quickly undertaken to assess the variety of initial conditions and flow outcomes possible for such PFEs when employed in the microgravity environment. We next describe testing of two terrestrial PFEs (CO₂ and HFC-227ea with N₂ pressurant) performed in two configurations (up-side-down and right-side-up) to bound the anticipated performance in microgravity. Finally, we compare the empirical PFE discharge data with the model and make predictions on the expected microgravity performance of the COTS PFEs.

A second consideration of using terrestrial PFEs in spacecraft is dispersion in confined areas. In terrestrial applications, suppressant is flooded into a volume with sufficient excess to ensure full extinguishment. In spacecraft, total quantity of suppressant is limited by available mass and volume constraints. Studies have shown that certain hydrofluorocarbons can exacerbate a fire when used at sub-extinguishment concentrations^{7,8}. A potential concern

with the use of hydrofluorocarbons in spacecraft is sub-extinguishment concentrations in the confined volumes of an avionics bay or within a rack, etc. that could result in more extreme fire than would nominally occur or would occur with a more traditional suppressant (e.g. water or CO₂). To evaluate this risk, wire bundles wrapped in a flammable P213 tape were ignited and exposed to varying concentrations of HFC-227ea in both air and the maximum contingency oxygen concentration expected in the spacecraft. Here we describe the test methods and discuss the observed differences in material burn rate as a function of suppressant concentration.

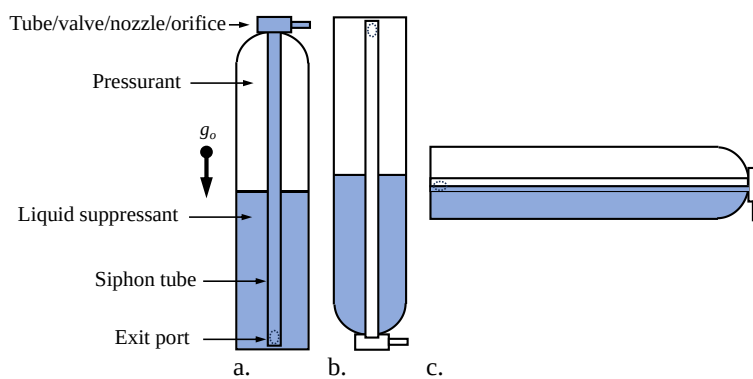


Figure 1. Sketches of 50% liquid-filled PFEs in a gravitational environment. a. right-side-up, b. up-side-down, and c. on side.

II. Terrestrial and Low-g PFE Analysis and Predictions

To establish a measure of quantitative expectations for COTS PFEs, a summary of analyses was undertaken to assess the variety of initial conditions and flow outcomes possible for such PFEs when employed in the microgravity environment. A numerical investigation was first performed to establish initial conditions, which were then used to compute order of magnitude tank characteristics such as natural frequency, stability, and viscous settling time via scale analyses and correlations. Three dynamical models were then outlined to address (1) pure liquid expulsion, (2) pure gas/vapor choked flow decompression, and (3) homogeneous mixed-phase expulsion. The primary microgravity fluid mechanics challenges of the assessment regard the critical initial condition of liquid in the PFE and the nucleation, expansion, and liquid entrainment capacity of gases and vapors within the PFE during the rapid decompression during operation. This effort sought to determine whether terrestrial tests with such orientations bracket performance expectations in a low-g environments.

A. Low-g PFE Liquid Configurations: Statics

For fire suppressing liquids like HFC-227ea, perfect wetting conditions are expected with low surface tension and low latent heat of vaporization, such that the equilibrium state of the liquid in the tank is highly likely to be bubble-free due to small but non-zero background g-levels and an inherent inability for free bubbles to become wall-bound. Thus, essentially bubble-free liquid configurations may be determined solely with knowledge of tank dimensions, liquid fill

fraction ϕ , g -vector, and fluid properties (liquid and gas/vapor density ρ and ρ_g , surface tension σ , and contact angle θ).

To this end we employ the SE-FIT software⁹ publicly available at <https://www.se-fit.com>. A highly configurable prebuilt model of the tank is developed as a plug-in for the code. An image of the GUI is provided in Figure 2 for a C-20 style PFE. Tank geometry, fluid properties, g -vector, liquid volume fill fraction and initial configuration are input by the user and the program solves for equilibrium free surface conditions. For a given configuration, the gravity amplitude and direction are then varied to determine the stability of the surface measured in terms of the Bond number, $Bo \equiv \rho g R^2 / \sigma$, as plotted in the inset at lower right in Figure 2. Values of Bo greater than these lead to topological changes in the fluid configuration within the tank—some of which may not place the liquid over the siphon tube. An infinite number of configurations are possible at zero- g with only a selection of SE-FIT-computed surfaces provided in Figure 3. The condition shown in Figure 3e demonstrates how a rightward $10^{-3}g_0$ acceleration disrupts the initial symmetric configuration of Fig. 3d creating a stratified topology that partially drains liquid from the base and lid regions, distributing liquid along the right side of the tank. Easily interpreted sketches of each numerical solution are provided in Figs. 3f-j.

We note that the 2-interface configuration of Figure 3d (and 3i) is a minimum energy configuration and thus more likely to arise than the others, though all surfaces are metastable and dependent on the most recent perturbations to the tank. For initial conditions, the microgravity configuration of Figure 3a compares with the terrestrial gravity configuration of Figure 1a, while that of 3b compares with 1b. However, the dynamics of these similar initial conditions differ in that the terrestrial application drives bubbles ever upward and droplets ever downward, which enhances performance when right-side-up, but retards performance when up-side-down. The microgravity application is expected to drive bubbles and entrained liquids in directions more in line with the expelled fluid. The most likely initial condition of Figure 3d (3i) complicates matters by distributing portions of bulk liquid over base and lid.

In part from the predictions in Figure 3, scaling laws are employed to determine g -stability, natural frequency, viscous settling time, and manually imparted Bond numbers $Bo \sim 1$ and Weber numbers $We \equiv \rho U^2 R / \sigma \sim 2$ predicting dynamic bubble size and configurations. We find that the minimum free surface energy configuration in the tank is indeed a two-interface configuration depicted in Figure 3d for most tank fill fractions including the 50% liquid filled PFE. High fill fractions lead to free bubbles in the bulk liquid (Ref. Fig. 3k) while low fill fractions lead to thin films that pool along base and lid (Ref. Fig. 3l).

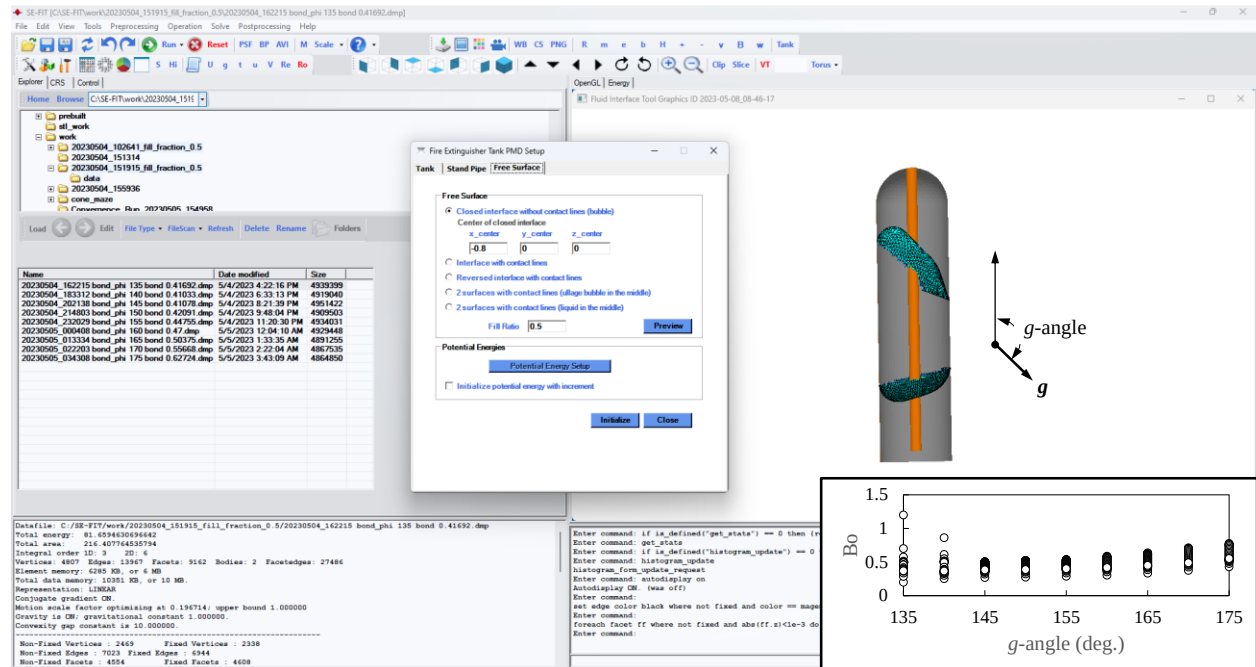


Figure 2. SE-FIT GUI of C-20 style PFE tank for computations of static equilibria and stability with respect to g -vector: parameter input window open in center with critical Bo vs. g -angle plot inset at lower right.

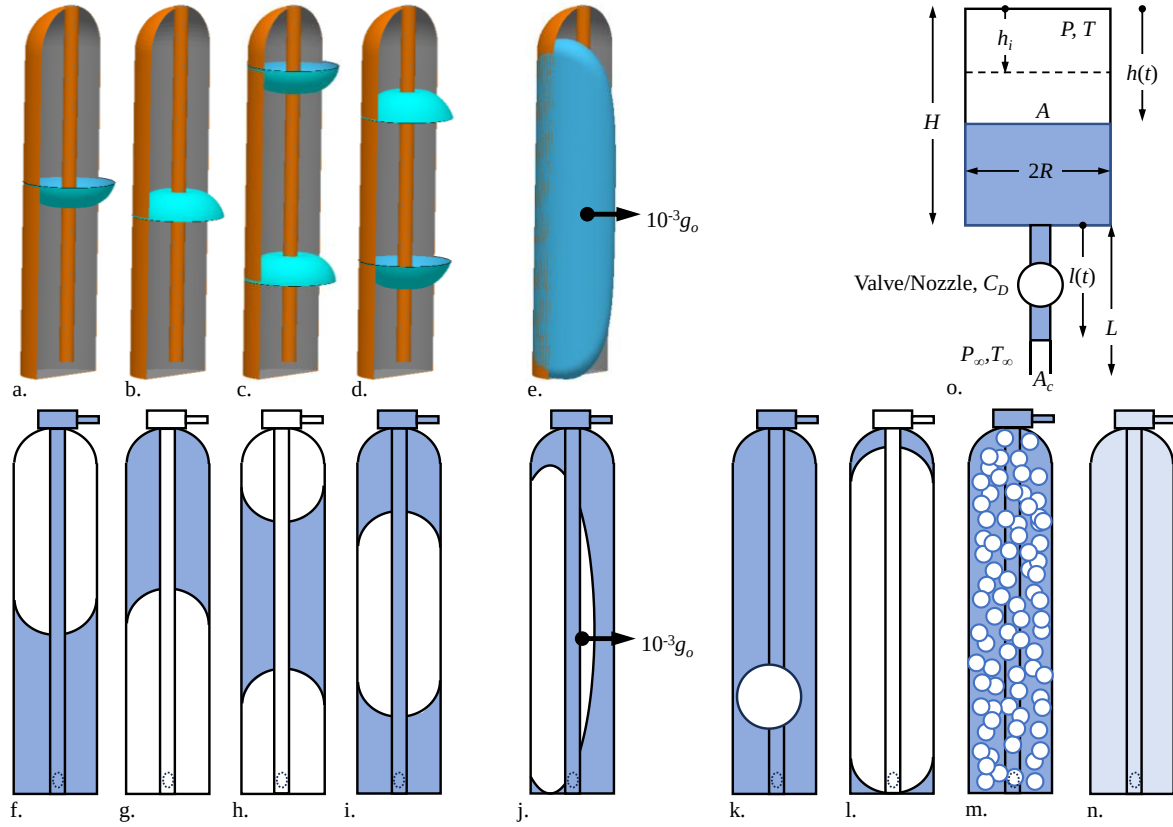


Figure 3. Selection of SE-FIT-computed configurations for 50% full C-20 style PFE tank with perfectly wetting HFC-227ea liquid in zero-g. Descriptions: a. liquid covering the base, b. liquid covering the lid, c. 2-interface configuration with centered liquid slug and gas/vapor covering base and lid, and d. 2-interface configuration with liquid covering base and lid. e. Asymmetric distortions for a rightward acceleration of $10^{-3}g_o$. f.-j. Respective simplified sketches of a.-e. k. Sketch of high fill fraction, l. low fill fraction idealizing liquid hold-up end state condition, m. unstable distributed bubble state, and n. density homogenized state of m. assumed in mixed-phase expulsion model. o. Annotated schematic of pure liquid expulsion model.

The other configurations sketched in Figures 3f-h are only locally stable. For characteristic tank dimensions and HFC-227ea fluid properties listed in Tables 1 and 2, low frequencies $\omega \sim (\sigma/\rho R^3)^{1/2} < 0.1$ Hz are likely to disrupt such interfaces at g-levels $> 10^{-4}g_o \sim \sigma/\rho g_o R^3$. Manually imparted g-loads at $\omega \sim 1$ Hz and $g \sim 2 \cdot 10^{-2}g_o$ break-up the interfaces into bubbles with characteristic diameters ~ 3 cm $\approx (4\sigma/\rho\omega)^{1/3}$, which if filling the tank produce a nearly uniform distribution of bubbles for a liquid fill fraction $\phi \approx 0.48$ (ref. Fig. 3m). These bubbles will eventually merge and re-form the general state of Figure 3i. Low frequency destabilizing accelerations agree between the present SE-FIT numerical solutions, previous theoretical analysis², and correlated data¹⁰. Perturbations are expected to decay via damped oscillations within the tank¹¹ within $\sim 0.005\rho R^2/\mu \approx 120$ s. Figure 3l shows the probable liquid hold-up end state of an idealized expulsion from the tank, provided significant bubble expansion and liquid entrainment does not remove more. Such hold-up liquid is also gradually expelled from the tank via thermally-limited evaporation, but over an essentially ineffectual period of time $\sim O(1 \text{ hr})$.

Table 1. Characteristic PFE tank dimensions.

Tank Style	Volume, V (mL)	Radius, R (m)	Height, H (m)	Eff. Nozzle Diam. (inch)	C_D , fit (dim'less)	Nom. Fill m_i (kg)
C-20	1750	0.065	0.132	0.27 (axial)	10.0	1.29
Amerex 322 CO ₂ (5lb)	3500	0.065	0.264	0.06 (2ea. Radial)	3.3	1.92
C-100	4250	0.065	0.320	0.27 (axial)	10.0	4.88

H is effective value based on V/A ; Nom. fill is liquid suppressant only, at $\sim 50\%$ V (confirmed by measurement subtracting calculated expellant mass); Smallest pinch point 'orifice.'

Table 2. Characteristic fluid properties employed (at $T \sim 300\text{K}$).

Fluid	Pressure P (Bar)	Density ρ (kg/m ³)	Density ρ_g (kg/m ³)	Surf. Tens. σ (N/m)	Viscosity μ (kg/m·s)	Contact Angle θ (deg.)
HFC-227ea	25.4	1354	28.9 (N ₂)	0.007	0.000184	~ 0
CO ₂	51	1101	90.9	0.0056	0.000053	~ 0
Novec 1230	25.4	1600	345	--	0.000624	~ 0

B. Approximate Theoretical Analysis: Dynamics

Several dynamic analyses are pursued following dramatically simplifying assumptions regarding initial liquid configuration and nature of the 2-phase mixing and flow phenomena within the tank during expulsion. Models for both terrestrial and low-g environments are pursued for comparison, correlation, and extrapolation. The independent parameters of the problem include initial orientation of the PFE with respect to g -vector, PFE and flow path dimensions (i.e., tank height H , tank radius R , area A_c for siphon tube, valve, nozzle, exit tube, and flow resistance coefficient C_D , initial temperature, pressure, fill fraction, and fluid properties. Dependent variables include transient fluid T , P , exit velocity U , gas/vapor density ρ_g , gas/vapor quality x and mass flow rate $\dot{m}$ expelled from the tank. Three models are pursued: pure liquid expulsion model (Ref. Fig. 2a, 3a, and 3f), pure gas/vapor expulsion model (Ref. Fig. 2b, 3b, and 3g), and homogeneous mixed-phase model (Ref. Fig. 3n). Certain post facto thermal/fluid assessments of assumptions are performed.

1. Pure Liquid Model: Only Liquid Expelled

When liquid covers the siphon tube inlet (base) of the PFE, barring significant bubble degassing and vaporization during the decompression, and neglecting capillary hold-up, nearly 100% liquid will be expelled from the tube/valve/nozzle by the expanding expellant gas and/or vapor. A simplified model for this scenario is sketched in Figure 3o, where relevant initial fluid configurations include Figs. 1a, 3f, 3i, and 3k. A tractable model for such expulsion assumes a quasi-steady 1-D force balance between tank pressure and siphon tube/valve/nozzle/tube viscous resistance (captured by A_c and C_D) that neglects liquid inertia (unsteady acceleration). The vapor/gas phase is treated with compressibility factor z (often chosen ≈ 1), the liquid is assumed to be isothermal, and an isothermal gas expansion is assumed at zeroth order with thermal impacts quantified at first order. Initial conditions include $h(0) = h_i$, $\rho_g(0) = \rho_{gi}$, $l(0) = L$, and $P(0) = P_i$. The resulting force balance yields

$$P_g - P_\infty = \frac{1}{2} C_D \rho_l \left(\frac{dl}{dt} \right)^2, \quad (1)$$

with tank pressure (linearization of adiabatic expansion assumed)

$$P = P_i \left(\frac{h_i}{h} \right)^\gamma \approx P_{gi} \frac{h_i}{h} \quad \text{where} \quad h_i \leq h \leq H \quad \text{and} \quad \gamma \approx 1.47 \text{ (i.e., for N}_2\text{)}. \quad (2)$$

An incompressible liquid volume balance is given by $A(dh/dt) = A_c(dl/dt) = A_c U$, when integrated establishes

$$h = \frac{A_c}{A} (l - L) + h_i. \quad (3)$$

Substitution of eqs. (2) and (3) into (1) yields the governing zeroth order nonlinear ODE

$$\frac{dh}{dt} = \frac{A_c}{A} \left(\frac{2P_{gi}}{C_D \rho_l} \right)^{1/2} \left(\frac{h_i}{h} - \frac{P_\infty}{P_{gi}} \right)^{1/2}, \quad (4)$$

subject to $h(0) = h_i$. From eq. (4) it is possible to establish a scale value for the liquid expulsion velocity $U \sim (A/A_c)dh/dt$. Noting that $h_i/h \sim O(1)$ and $P_\infty/P_{gi} \ll 1$, for HFC-227ea we estimate

$$U \sim \left(\frac{2P_{gi}}{C_D \rho_l} \right)^{1/2} \sim \left(\frac{2 \cdot 25.4 \cdot 101000}{C_D 1354} \right)^{1/2} \sim O(20 \text{ m/s}). \quad (5)$$

From experimental demonstrations we find $U \sim O(20 \text{ m/s})$, such that for known A_c we may use eq. (5) to find $C_D \sim O(10)$ for such PFEs. Eq. (4) may be rearranged and solved to find the implicit solution

$$t = \frac{h_i}{K \epsilon^{3/2}} \left\{ \tan^{-1} \left(\frac{1-\epsilon}{\epsilon} \right)^{1/2} - \tan^{-1} \left(\frac{h_i/h-\epsilon}{\epsilon} \right)^{1/2} + \epsilon^{1/2} \left[(1-\epsilon)^{1/2} - \frac{h}{h_i} \left(\frac{h_i}{h} - \epsilon \right)^{1/2} \right] \right\}, \quad (6)$$

Where $K \equiv (A_c/A)(2P_{gi}/C_D \rho_l)^{1/2}$, and $\epsilon \equiv P_\infty/P_{gi}$. From eq. (6), $t(h)$ is inverted to find $h(t)$ and determine

$$U \approx \frac{A}{A_c} \frac{dh}{dt} \quad \text{and} \quad \dot{m}_l = \rho_l A_c U = \rho_l A \frac{dh}{dt} \quad \text{and} \quad \dot{m}_l = (H - h) \rho A. \quad (7)$$

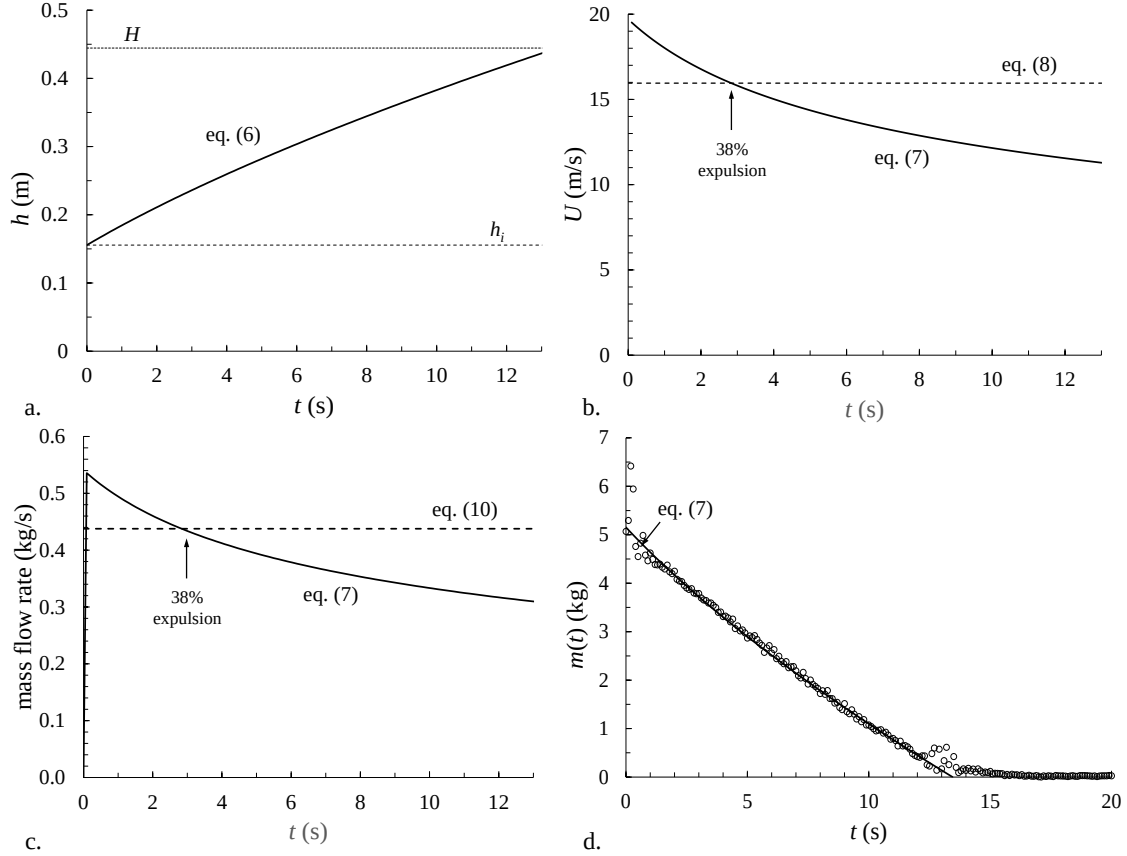


Figure 4. a. Eq. (6) solved and inverted to find $h(t)$, which is used to solve b. eq. (7) for U , c. $\dot{m}$, and d. liquid mass in tank m . Data for HFC-227ea C-100 tank test are overlaid in d. with an excellent single parameter fit achieved for $C_D = 10.0$ for the initially 65% liquid-filled tank.

We note that for an HFC-227ea, C-100 style tank (Ref. Tables 1 and 2): $h_i = 0.229$ m, $H = 0.444$ m, $P_i = P_{gi} = 25.4$ Bar, $P_\infty = 1$ Bar, $C_D \sim 9.5$, $A_c = (\pi/4) 0.005^2 = 2 \cdot 10^{-5}$ m², $A \approx \pi 0.065^2 = 0.0131$ m²,

$$K \equiv \frac{A_c}{A} \left(\frac{2P_{gi}}{C_D \rho_l} \right)^{1/2} = \frac{2 \cdot 10^{-5}}{0.0131} \left(\frac{2 \cdot 25.4 \cdot 101000}{9.5 \cdot 1354} \right)^{1/2} \approx 0.03 \quad \text{and} \quad \epsilon \equiv \frac{P_\infty}{P_{gi}} = \frac{1}{25.4} = 0.039.$$

For these values we plot $h(t)$ from eq. (6), and U , $\dot{m}$, and m from eq. (7). We note that a value of $C_D = 9.5$ results in a 13.4 s drain time for the initial condition of Figure 4a, which agrees well with empirical drain time observed from test data presented in Figure 4d. Simpler explicit forms are complicated by unwieldy expansions of eq. (6) for $\epsilon \ll 1$. Because the function appears to be somewhat linear we expect that the two-interface model of Fig. 3i is likely to expel half its contents in half this time, ~ 6.7 s, leaving the remaining held-up liquid to slowly evaporate in time.

Modifying eq. (5), a quick estimation of expulsion velocity may be found using

$$U_{ave} \sim \left(\frac{2\Delta P_{ave}}{C_D \rho_l} \right)^{1/2} \approx 15.9 \text{ m/s}, \quad (8)$$

which is presented in Figure 4b, where

$$\Delta P_{ave} \equiv \frac{P_i}{2} \left(1 + \frac{h_i}{H} \right) - P_\infty \approx \frac{P_i}{2} \left(1 + \left(\frac{h_i}{H} \right)^Y \right) - P_\infty, \quad (9)$$

the latter which employs the ideal gas law for the pressure for the adiabatic expansion, which when substituted into eq. (8) predicts $U \sim 15.1$ m/s within less than 5% from isothermally assumed prediction in eq. (8). This approximate value for U permits explicit approximations for average mass flow rate via

$$\dot{m}_{lave} \approx \rho_l U A_c \sim A_c \left(\frac{2\rho_l \Delta P_{ave}}{C_D} \right)^{1/2} \approx 0.44 \text{ kg/s}, \quad (10)$$

as shown in Figure 4c. Thus, tank drain times are readily estimated as $t_{drain} \approx m_{init}/\dot{m}_{lave} = 11.8$ s, which is within 12% of the measured value 13.4 s observed in Figure 4d.

2. Pure Gas/Vapor: Only Compressible Gas/Vapor Expelled with Thermal Considerations

Choked flow conditions are experienced when gas/vapor initially covers the exit port as sketched in Figures 1b, 3g, and 3h. For pure gas and/or vapor expulsion the flow is choked if ($\gamma \approx 1.47$)

$$P_{tank} \geq P_{\infty} \left(\frac{\gamma+1}{2} \right)^{\gamma/(\gamma-1)} \approx 1.93 P_{\infty}, \quad (11)$$

which is true for much of the PFE operation. Assuming a choked ideal gas the expulsion mass flow rate is given by¹²

$$\dot{m}_g = c_d A_c \left(\gamma \rho_o P_o \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \right)^{1/2}, \quad (12)$$

where $c_d \sim 0.8$ is a discharge coefficient similar to flow resistance coefficient C_D . Computing Δm for the initial and end states for N₂ in a C-20 50%-filled HFC-227ea tank, the above may be used to estimate choked flow time ~ 0.1 s, which is small indeed due to the relatively large tank nozzle exit area A_c . When the flow is no longer choked, we estimated the tank depressurization time using time constant to find

$$\tau = \frac{V_{g-v}}{c_d c_o A_c} \left(\frac{\gamma+1}{2} \right)^{(\gamma+1)/2(\gamma-1)} \approx 1 \text{ s}, \quad (13)$$

Where V_{g-v} is the gas/vapor volume within the tank (i.e., 50% V) and speed of sound $c_o = (\gamma R T_o)^{1/2}$. The low value for τ again suggest a rapid expulsion for both choked and unchoked portions of the flow. We note that the pressure in the tank may be determined by

$$P = P_o \left(1 + \left(\frac{\gamma-1}{2} \right) \frac{t}{\tau} \right)^{2\gamma/(1-\gamma)}. \quad (14)$$

Thus, under the idealized assumption of no liquid entrainment due to the gas/vapor expansion and expulsion, we expect the configuration of liquid covering the lid to depressurize in less than a few seconds without appreciable liquid fire suppressant expulsion.

Following the pure gas expulsion, the liquid will begin and continue to evaporate and expel itself as a vapor over a longer thermally-limited period. Because the liquid is initially superheated, the excess sensible heat of the liquid and tank will provide ready heat to vaporize an initial mass of the liquid as given by

$$m_{levap} = \left((mc_p)_l + (mc_p)_{tank} \right) (T_i - T_{sat}) / h_{fg} \approx 0.94 \text{ kg}, \quad (15)$$

which is $\sim 70\%$ of the total liquid contained (1.5 kg charge): $m_l = 1.35$ kg, $m_{tank} \approx 4$ kg, and $c_{ptank} = 566$ J/kgK. This preliminary evaporation is likely to be violent aiding significantly in the expulsion of liquid by the entraining vapor created as well as dissolved gas bubble degassing. However, if we assume no bubbles are created, the rest of the liquid mass must evaporate over time and is limited largely by low thermal conductivity of the liquid and poor forced/natural convection in the low-g environment. Assuming no enhancements due to bubble production, mixing, ingestion, and entrainment, ignoring the presence of the tank wall one computes thermal time scales associated with conduction within the respective quiescent liquid t_{cond} and convection-limited heat transfer t_{conv}

$$t_{cond} \sim \frac{R^2}{3\alpha} \sim 546 \text{ min} \quad \text{and} \quad t_{conv} \sim \frac{m h_{fg}}{HTC \cdot A_{tank} (T_{\infty} - T_{sat})} \sim 1128 \text{ min}, \quad (16)$$

where $\alpha = k/\rho c_p$ the thermal diffusivity, $m = m_i - m_{levap}$, $T_{sat} = -16^\circ\text{C}$, $h_{fg} = 132,582$ J/kg, $k = 0.069$ W/m $^\circ\text{C}$, $c_p = 1185$ J/kg $^\circ\text{C}$, $A_{tank} \sim 2\pi RH$, and $HTC = 1.5$ W/m ^{2} $^\circ\text{C}$. It is clear from these estimates that, without the aid of significant internal mixing due to bubble production and liquid entrainment, internal conduction and external convection are quite low to the extent that hours are required for expulsion of the HFC-227ea vapor by evaporation only. However, it is also clear that significant local sensible heat is available in the liquid and tank to evaporate a large portion of the decompressed liquid. Expanding bubbles produced during this process are highly likely to entrain liquid as they are expelled from the tank.

3. Mixed-Phase Model: Only Homogeneous Gas/Vapor/Liquid Mixture Expelled

Nucleating, degassing, and vaporizing bubbles within the PFE are capable of entraining liquid upon exiting the device. Such bubbles may be produced by any combination of initial interface configurations, destabilizing perturbations imparted to the device during operation, and gas and vapor bubbles produced during the rapid decompression. As an approximate analytical approach, we assume that the fluid phases are well-mixed to the point of creating a homogeneous compressible fluid phase with uniform properties of the mixture assessed by the time-dependent quality $x = V_g/V$. Sketches of this assumption are shown in Figures 3m-n. A more complete list of assumptions includes uniform quality x and ρ , compressibility z such that gas constant $R_{mix} = zR$, nozzle resistant coefficient C_D and device exit area A_c same for liquid, gas/vapor, and mixed-phase, known V , initial quality x_i , density ρ_i , P_i , T_i , and isothermal

properties. Transient dependent variables include mixture P , x , ρ , and exit velocity U . A quasi-steady force balance is employed neglecting unsteady inertia, gravity, and cooling due to adiabatic expansion and Joule-Thomson effect.

As applied to the Pure Liquid Model, a 1-D force balance again combining all viscous resistance effects of siphon tube, valve, nozzle, and exit tube into one resistance coefficient C_D yields

$$P - P_\infty = \frac{1}{2} \rho C_D U^2, \quad (17)$$

where mixture density and mixture vapor/gas density is ‘ideal’ with compressibility z are

$$\rho = x\rho_g + (1-x)\rho_l \quad \text{and} \quad \rho_g = P/zRT. \quad (18)$$

Gas/vapor quality x and mass balance are defined by

$$\frac{\partial x}{\partial t} = (1-x) A_c U / V \quad \text{and} \quad \frac{\partial \rho}{\partial t} = -\rho A_c U / V. \quad (19)$$

Equations (17) – (19) are subject to P_i , ρ_i , x_i , and ρ_{gi} at $t = 0$. Integrating eqs. (19) and substituting into eqs. (18), and finally eq. (17) yields the governing implicit integro-differential equation for exit velocity

$$U = \left(\frac{2(P-P_\infty)}{\rho C_D} \right)^{1/2} = \left[\frac{2 \left(\frac{zRT(\rho_l(1-x_i)-\rho_i)}{1-x_i-1/E} - P_\infty \right)}{C_D(x\rho_g + (1-x)\rho_l)} \right]^{1/2}, \quad (20)$$

$$x = 1 - (1-x_i)E; \quad \rho_g = \frac{\rho_l(1-x_i)-\rho_i}{1-x_i-1/E}; \quad P = zRT \left(\frac{\rho_l(1-x_i)-\rho_i}{1-x_i-1/E} \right); \quad E \equiv \text{Exp} \left[-\int_0^t \frac{A_c U}{V} d\hat{t} \right]. \quad (21)$$

For a C-20 HFC-227ea tank, we note that for $x_i \approx 0.5$, $P_i \approx 25.4$ Bar, $R_{N2} \approx 297$ J/kg·K, $z \approx 1$, $T \approx 300$ K, $P_\infty \approx 1$ Bar, $C_D \approx 9.5$, and $A_c \approx 0.20$ cm², eq. (20) must be solved numerically and then used to determine the mass flow rate

$$\dot{m} = \rho A_c U = A_c \left(\frac{\rho(P-P_\infty)}{C_D} \right)^{1/2} \quad \text{and} \quad \dot{m}_{ave} \approx A_c \left(\frac{\rho_{ave} \Delta P_{ave}}{C_D} \right)^{1/2}, \quad (22)$$

The latter providing an estimate of the average mass flowrate $\dot{m}_{ave}$ and characteristic time $\tau_x \approx m_{tot}/\dot{m}$. These results are presented in Figure 5.

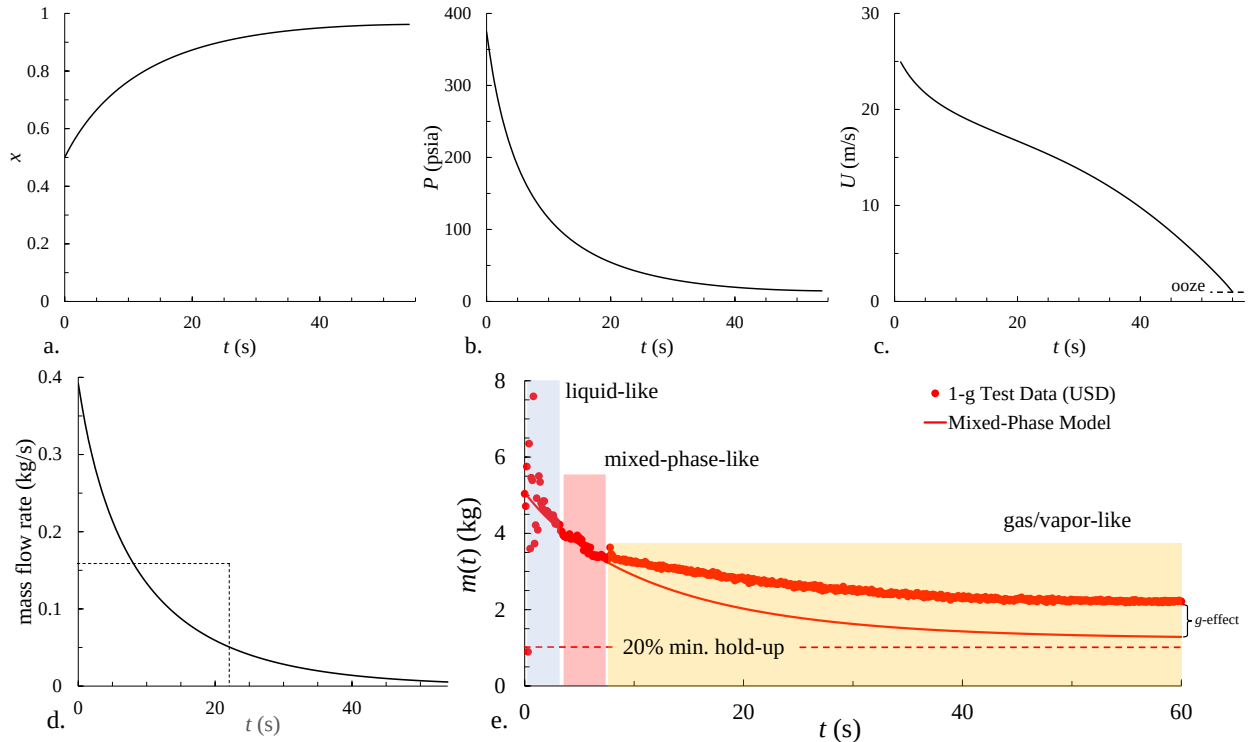


Figure 5. Mixed-phase model predictions for HFC-227ea in 65%-filled C-100 PFE: a. tank quality x eq. (21), b. pressure P eq. (21), c. exit velocity U eq. (20), and d. mixture density ρ , eq. (18). e. Mixture mass in tank $m = m_i - \int \dot{m} dt$ with test data compared (red circles).

Values for $\dot{m}_{ave}$ and τ_x are identified in Figure 5d. Many of the details of the analysis may be overlooked in favor of this simple form which predicts average (half-) mass flow rate within 16% and characteristic average (half-) time constant within 2%. All trends in Figure 5 are expected except for the velocity history in Figure 5c, which possesses an inflection as the pressure driving force adjusts weakly and non-linearly with mixture quality. The ‘ooze’ limit is identified in the figure where liquid no longer has ample inertia to spray out of the PFE but rather oozes out, remaining attached to the nozzle by capillary forces. We estimated this amount to be < 10 mL, but with entrained bubbles could appear much larger.

Mixture mass $m = m_i - \int \dot{m} dt$ is plotted in Figure 5e using a solid red line and compared to test data for the HFC-227ea C-100 up-side-down tank using solid red symbols. Despite the single homogeneous mixture assumption, the mixed-phase model appears to capture single-phase liquid-, mixed-phase-, and single-phase gas/vapor-like regimes observed during the tests. The 20% maximum low-g hold-up prediction is included as a red dashed line. The ‘g-effect’ of the data is identified in the figure where gravity is assumed to retard liquid expulsion in the up-side-down tests which would not occur at reduced-g conditions (Ref. Fig. 4d).

III. Terrestrial Analysis Correlation

Correlation of the terrestrial analysis described above was accomplished through empirical testing of two terrestrial portable fire extinguishers, each containing unique suppressant. Each PFE was tested in a right side up (RSU) and upside down (USD) configuration to provide extrema flow scenarios of the PFEs in 1-G, as zero/micro-G testing was not possible. RSU testing sought to characterize “best case” PFE discharge performance based on the assumption that the maximum quantity of suppressant would discharge the tank in a RSU configuration. USD testing sought to characterize “worst case” PFE discharge performance based on the assumption that the minimum quantity of suppressant would discharge the tank. Materials and methods of this testing and a comparison of the analyses with empirical data is provided below.

A. Terrestrial PFE Test Materials and Methods

1. Terrestrial Portable Fire Extinguishers

Two terrestrial PFEs were selected for testing. The first was an Amerex Model 322 5lb CO₂ B&C extinguisher. The standard nozzle provided with the PFE was replaced with a custom nozzle containing two radial holes. The second PFE was a Sea-Fire C-100 10.75lb FM-200 (HFC-227ea) extinguisher. The standard nozzle was replaced with a custom axial flow nozzle with a 0.27 inch diameter. Custom nozzles were selected based on experimental configurations of interest for future vehicles.

2. PFE Test Fixture

The PFEs were each tested while constrained within an insulated container, to provide a more known and controlled environment useful for model correlation. The test apparatus, as shown in Figure 6 provided guides that limited motion to only translation along the gravity vector, providing reaction loads/torques in all other directions, and allowing measurement of the mass of the PFE as a function of time. To prevent blowback of the suppressant within the container, a custom adapter was designed to provide a conduit from the PFE nozzle to the outside of the test fixture. Each PFE was outfitted with 3 thermocouples located at the base, midway along the tank length, and on the nozzle. An actuator was designed to provide remote, instantaneous, and controlled discharge of the PFE. Two high speed cameras, a Phantom Flex4k and a Phantom S990 (Vision Research Inc. Wayne, NJ), were used to capture discharge in both RSU and USD configurations. Mass measurements were taken using a load cell and were collected real-time using National Instruments data acquisition and controlled with custom Labview software.

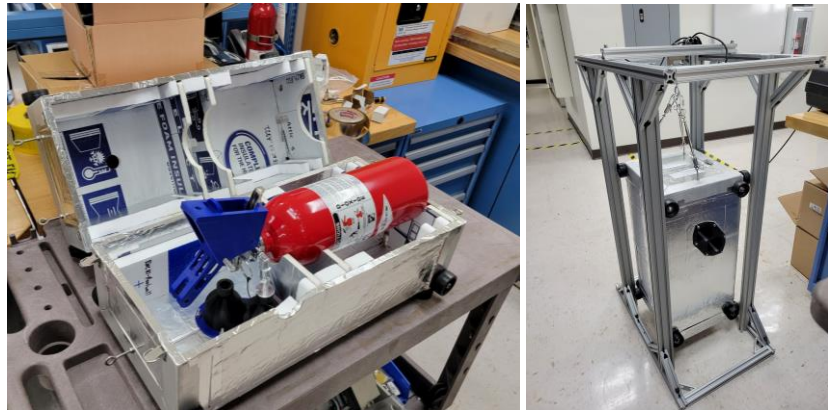


Figure 6. PFE in insulated container (left) and when assembled into test fixture (right).

3. RSU and USD Test Methods

Each PFE was installed into the test fixture in either the RSU or USD configuration and outfitted with thermocouples. The test fixture was placed in the test location and allowed to equilibrate for a minimum of 30 minutes. To begin testing, the cameras were set to record and the PFE was remotely actuated. Data was collected until the PFE no longer released suppressant (between 35 and 298 seconds). RSU discharge of a C-100 HFC-227ea PFE is shown in Figure 7.



Figure 7. Right-side-up discharge of C-100 HFC-227ea PFE.

B. Comparisons of Analyses with Experiments

Pure liquid and mixed-phase models are overlayed in Figure 8 for 61% liquid-filled HFC-227ea C-100 and 56% liquid-filled CO₂ C-20 PFEs with select data collected for RSU and USD tests. We note that the pink-shaded regions suggest the variety of low-g outcomes expected depending on initial condition—the region is bracketed at left by the pure liquid model as correlated to the RSU test data, while bracketed at upper right by the mixed-phase model. The mixed-phase model over-predicts the mass expulsion rate $\dot{m}$ terrestrial USD data for HFC-227ea as expected but under-predicts such data for CO₂. It is conjectured that the former is due to gravity holding up significant liquid in the lid region while the latter is due to the near triple point nature of the CO₂ leading to significantly higher rates of vaporization taking place throughout the tank, maintaining higher tank pressures, and efficiently driving out greater amounts of liquid from numerous sources of expanding CO₂ vapor. Such effects are addressed in the mixed phase model.

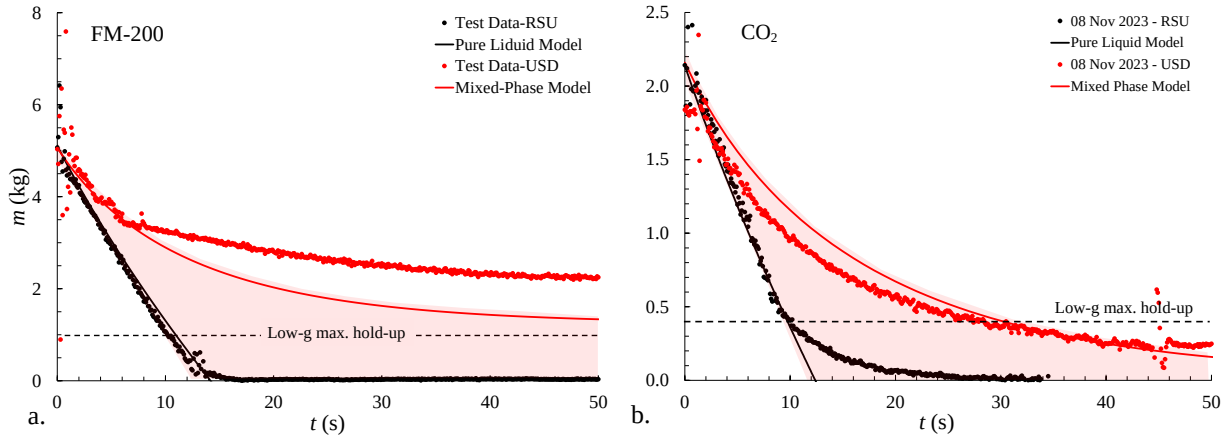


Figure 8. Comparison of pure liquid and mixed-phase models with test data for a. HFC-227ea C-100 ($m_{il} = 4.09$ kg, $\phi = 0.61$, $C_D = 10$, nozzle 0.27 in axial) and b. CO₂ Model 322 PFEs ($m_{il} = 2.16$ kg, $\phi = 0.56$, $C_D = 3.3$, nozzle 0.06 in radial (2 ea)). Pink-shaded regions suggest a variety of low-g outcomes depending on initial conditions.

In general, the pure liquid expulsion model yields closed form expressions accurate to within 15% with neglected thermal effects estimated to be $< 5\%$. Numerically determined initial conditions suggest that, in the absence of entrainment, a conservative minimum of $\sim 40\%$ of the liquid will be expelled for the two-interface initial condition (ref. Fig. 3i) in low-g at nearly the terrestrial RSU rate. A conservative maximum is $\sim 80\%$ for the single interface initial condition (ref. Fig. 3f) in low-g at nearly the terrestrial RSU rate. The model identifies a single empirical fitting parameter $A_c/C_D^{1/2}$, and since A_c is approximately known a priori, C_D is varied providing favorable agreement between theory and RSU terrestrial test.

For HFC-227ea, when gas/vapor initially covers the siphon tube inlet of the PFE, the expulsion flow is choked for typically < 1 s followed by an unchoked flow for another ~ 1 s after which the N₂ expellant is exhausted. In low-g, without nucleation, degassing, boiling, and liquid entrainment, thermal conduction and convection time scales require hours to evaporate the remaining liquid. However, the sensible heat sources of the liquid and tank are capable of vaporizing $\sim 70\%$ of the liquid, suggesting that rapid decompression could produce a significant number of expanding bubbles which will entrain excess liquid as they are expelled from the tank and that pure liquid and pure gas/vapor models will devolve into a ‘mixed-phase model’ of varying degree. Hence the shaded regions in Figure 8.

The homogeneous mixed-phase model targets expulsion scenarios where sensible heat in the liquid and tank leads to dramatic bubble production within the liquid during the rapid decompression. These bubbles entrain significant liquid as they expand and leave the tank. These bubbles also carry with them the expellant, thus reducing the efficiency of expulsion. The predicted expulsion time is approximately 4 to 5 times longer than for pure liquid expulsion. The mixed phase leaves as a spray compared with a liquid jet for the pure liquid expulsion. The expulsion velocity is on the same order as for the pure liquid expulsion, $\sim O(10 \text{ m/s})$. For less volatile suppressant like HFC-227ea, during the final stages of mixed-phase expulsion, a liquid blob ($< 10 \text{ mL}$) can ooze out of the tank. This does not occur for pure liquid expulsion. Wieldy approximate closed-form solutions are found for U_{ave} , $\dot{m}_{ave}$, and expulsion time τ_x .

Thus, the performance of the PFE depends entirely on initial liquid configuration in low-g. A two-interface configuration is the most likely initial configuration for the PFE—liquid covering the base and lid with a large single ullage between (ref. Fig. 3d, 3i). Fortunately, significant sensible heat is available in the liquid and PFE tank masses to evaporate up to 70% of the liquid, suggesting that significant boiling and liquid entrainment is expected during the decompression and expulsion. As a result, in keeping with the HFC-227ea example, a brief pure liquid expulsion (jet, $\sim 40\%$, $\sim 5 \text{ s}$) is likely to be followed by a mixed phase expulsion (spray, $\approx 40\%$, $\sim 25 \text{ s}$), combining to expel between 40% and 80% of the HFC-227ea mass within $\sim 30 \text{ s}$. Based on this assessment, the initial state of Fig. 3i rapidly converts to the state of Figure 3m, modeled by mixed-phase expulsion (ref. Fig. 3n) with expectations of up to 80% liquid expulsion within 25 s—single-phase liquid jet followed by mixed phase spray. For the worst-case initial condition of gas over the exit port, without boiling, hours are required to evaporate and expel the liquid in vapor state. Worst case liquid hold-up in the tank of $< 20\%$ is expected to be unavoidable and will require hours to evaporate and expel. CO_2 PFEs do not employ an expellant, possess higher initial thermal energy for rapid bubble formation and liquid entrainment, and are thus able to expel the extinguishing agent at higher rates than predicted by the mixed-phase model (ref. Fig. 8b).

IV. HFC-227ea Fire Exacerbation and Extinguishment Limit Investigation

Testing was conducted to determine the effect of sub-extinguishment concentrations of HFC-227ea on an established fire. A comparison was made of burn rates in the absence of suppressant and in varying concentrations of HFC-227ea. Details of the test are provided below.

A. Materials and Methods

To evaluate how varying HFC-227ea impacts burn rates and extinguishment, testing was conducted on realistic flammable materials that might be found in cabin environments. P213 acrylic glass cloth tape is nonflammable when used on a metallic substrate but highly flammable on non-metal substrates such as when it is used as a wring overwrap. Because of this misunderstanding in application specific flammability impacts, P213 has unfortunately been found used in wire overwrap configurations across various programs. Because of this common mistake, P213 was selected for this study as a highly flammable realistic material that may be present in a space cabin environment.

For P213 testing, two sample configurations were used. The first as of a single 16AWG twisted pair (M27500-16WR2U00) wire overwrapped with P-213 Tape. The second was of a bundle of four 16AWG twisted pair (M27500-16WR2U00) wires overwrapped with P-213 Tape. Single wire configurations are not realistic but considered a worst case configuration with respect to flammability. A four bundle pair can realistically be found across wiring and is also conservative for limiting heat sinks when evaluating flammability performance. Limited testing was also performed with cotton T-shirt material (Hanes Beefy T) as this is a common undergarment material worn by astronauts that can realistically be found as a flammable material in the cabin.

The test samples were fixtured inside of a flow tunnel for upward flammability testing, as shown in Figure 9. Flow was established with a mixture of nitrogen and oxygen targeting an initial cabin condition of either 24.1% oxygen or 20.9% oxygen (to cover the range of

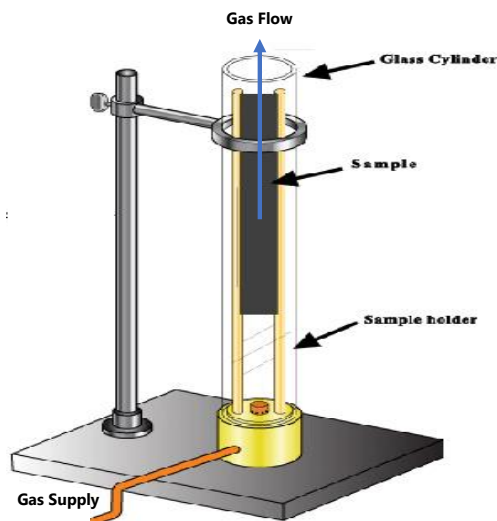


Figure 9. Upward flammability test fixture. Oxygen and HFC-227ea flow rates controlled by flow controller with adjustments for material density.

nominal ISS oxygen concentrations) with balance of nitrogen at 14.7psia. An oxygen analyzer was used as confirmation of concentration in addition to mass flow calculations. The concentration was measured in the flow prior to entering duct and flow velocity was also measured via hot wire anemometer prior to test each day to confirm flow was at 40 mm/s. Test articles were ignited using 5 wraps of 22-gauge Kanthal wire at 10A.

After the initial fire at starting cabin conditions was stabilized and propagated ~3 inches, HFC-227ea was introduced at a target concentration and fire evaluated for burn rate exacerbation and extinguishment. This method was repeated at increasing HFC-227ea concentrations until five replicates were obtained at a given HFC-227ea concentration with successful extinguishment. Baseline burn rate characterizations were also performed in which the test sample was allowed to burn full length in its initial cabin condition (24.1% oxygen or 20.9% Oxygen) in order to establish the materials “Free burn” baseline burn rate.

Mass flow controllers were used to meter the appropriate flows and obtain the desired mixture. HFC-227ea density is much greater than that of gaseous nitrogen or oxygen and had to be accounted for when calculating introduced HFC 227ea concentrations. Published data reports HFC 227ea vapor density @ 25°C (77°F) and 1 atm, as 7.148 kg/m³ (0.4462 lb/ft³) compared to that of air (1.293 kg/m³ (0.0807 lb/ ft³)) for which the mass flow controller was calibrated. The ratio of densities was calculated to approximately 5.528 and applied to the desired HFC 227ea volumetric flow rate to achieve target HFC-227ea relative concentration. Images at key points of a test are shown in Figure 10.

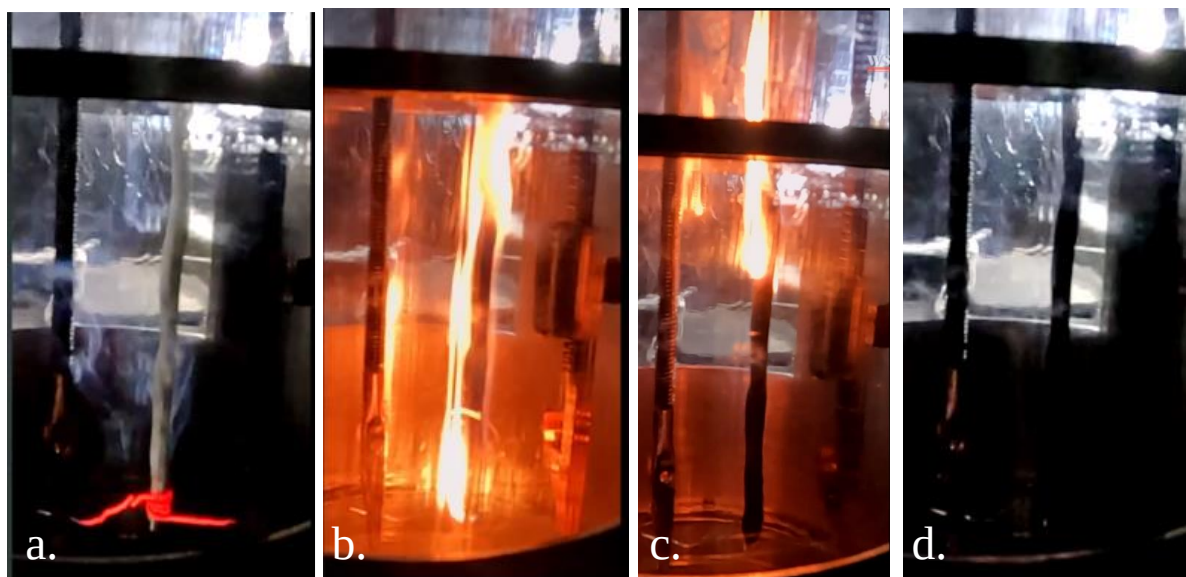


Figure 10. P213 wrapped wire at 24.1% O₂ and 14.7 psia initial conditions followed by 11.2% HFC-227ea extinguishment. Images show a) P213 wrapped wire in flow tunnel with initial heating of igniter, b) propagation at 24.1% O₂ and no suppressant, c) initial introduction of 11.2% HFC-227ea (burn rate increases), d) extinguishment 11 seconds after HFC-227ea introduction.

B. Test Results and Discussion

This test series was successfully able to establish extinguishment limits for P213 wrapped wires. Though testing was performed with two bundle sizes, little difference was noted between extinguishment limits when starting with 24.1% Oxygen conditions. For a single wire P213 overwrap configuration (Table 3), levels of 10.3% HFC 227ea were required before consistent extinguishment was observed.

For a four-wire bundle P213 overwrap configuration (Table 4), levels of 10.8% HFC 227ea were required before consistent extinguishment was observed. Extinguishment limit for the single wire configuration was found to be with extinguishment limit established. When examining cotton (Table 4), an extinguishment limit was not established. Cotton continued to burn despite the introduction of 30% HFC 227ea.

Table 3. Burn rate, extinguishment time, and consistent extinguishment thresholds for single wire wrapped in P213 tape when exposed to varying concentrations of HFC-227ea. Data shown for ambient environments of 24.1% (left) and 20.9% (right) oxygen. *Actual concentrations of HFC-227ea may vary. Concentrations displayed have been rounded up.

Single Wire Wrapped in P213 Tape												
24.1% O2							20.9% O2					
HFC 227ea*	Burn Rate		Ext. Time	Tests w/ Successful Extinguishment	Total Number of Tests	Consistent FM200 Extinguishment Observed	Burn Rate		Ext. Time	Tests w/ Successful Extinguishment	Total Number of Tests	Consistent FM200 Extinguishment Observed
	Free Burn @ 24.1%	Post HFC 227ea					Free Burn @ 20.9%	Post HFC 227ea				
(%)	(mm/s)	(mm/s)	(s)	(%)		(%)	(mm/s)	(mm/s)	(s)	(%)		(%)
3	3.5	--	--	--	--	10.3	2.6	--	--	--	--	9.4
4		5.3	--	0.0	3			--	--	--	--	
5		8.4	--	0.0	3			--	--	--	--	
6		8.7	--	0.0	3			5	--	0.0	2	
7		8.6	--	0.0	2			4.3	27.3	60.0	5	
8		8.1	18	16.7	6			7.5	23	50.0	2	
9		6.7	--	0.00	13			4.8	38.8	75.0	16	
10		5.3	22.9	77.8	9			3.6	23.8	100.0	11	
11		4.7	28.3	100.0	9			2.9	17	100.0	1	
12		3.5	20.5	100.0	2			--	--	--	--	
13		--	--	--	--			--	--	--	--	

Table 4. Burn rate, extinguishment time, and consistent extinguishment thresholds for four wires wrapped in P213 tape (left) and Hanes Beefy T cotton (right) when exposed to varying concentrations of HFC-227ea. Data shown for ambient environments of 24.1%. *Actual concentrations of HFC-227ea may vary. Concentrations displayed have been rounded up.

Four Wires Wrapped in P213 Tape							Hanes Beefy T (Cotton Shirt Material)			
24.1% O ₂							24.1% O ₂			
HFC 227ea*	Burn Rate		Ext. Time	Tests w/ Successful Extinguishment*	Total Number of Tests	Consistent FM200 Extinguishment Observed	HFC 227ea*	Tests w/ Successful Extinguishment	Total Number of Tests	Consistent FM200 Extinguishment Observed
	Free Burn @ 24.1%	Post HFC 227ea								
(%)	(mm/s)	(mm/s)	(s)	(%)		(%)	(%)			(%)
3		--	--	--	--		7	--	--	
4		--	--	--	--		10	0.0	1	
5		--	--	--	--		13	0.0	1	
6		--	--	--	--		16	0.0	1	
7		--	--	--	--		19	50.0	2	
8		--	--	--	--		20	50.0	2	
9	3.6	--	--	--	--	10.8	21	0.0	1	>30.0
10		5	20.3	100.0	6		22	0.0	1	
11		3.5	14	80.0	5		24	0.0	1	
12		3.1	23.6	100.0	7		26	0.0	1	
13		2.5	41	100.0	1		28	100.0	1	
							29	0.0	1	
							30	50.0	2	

This test series was also successful in its ability to evaluate fire exacerbation impacts of HFC 227ea. Test sample burn rates were consistently found to aggravate with HFC 227ea introduction prior to reaching extinguishment limits across both starting conditions and for both wire configurations. For 24.1% Oxygen initial conditions and single wire config, burn rates were found to aggravate as low as 4% HFC 227ea and double in the 5-8 % HFC 227ea range. For 20.9% Oxygen initial conditions and single wire config, burn rates were also found to aggravate with 5% HFC 227ea concentrations and double in the 8 % HFC 227ea range.

V. Summary and Outlook

Current requirements for PFE performance on ISS and in visiting vehicles require oxygen depletion to <10.5% O₂ in the target volume within one minute. For non-depleting suppressants, such as hydrofluorocarbons, a requirement to extinguish the fire within one minute is specified. The use of terrestrial PFEs to achieve these conditions in microgravity require consideration of the PFE design, particularly for multi-phase systems, and the suppressant used. In this effort, two types of terrestrial PFE were modeled and tested. Both PFE tank designs included a dip tube that maximizes suppressant uptake in 1-g. The first was an HFC-227ea liquid PFE with gaseous nitrogen as the pressurant. The second was a liquid CO₂ PFE with gaseous CO₂ headspace. A mixed phase model was validated with test data and showed that the performance of the PFEs depend entirely on the initial liquid configuration in low-g. A two-interface configuration is the most likely initial configuration for the PFE, wherein liquid covers the base and lid with a large single ullage in between. If discharged in microgravity, the HFC-227ea PFE would be expected to expel between 40% and 80% of the suppressant mass within ~ 30 s. After expulsion of the nitrogen pressurant, the remaining liquid hold-up in the tank of < 20% is expected to be unavoidable and will require hours to evaporate and expel. CO₂

PFEs are able to expel the extinguishing agent at higher rates than HFC-227ea and higher rates than predicted by the mixed-phase model, but will still experience similar quantities of hold-up. Vehicle designs planning the use of multi-phase PFEs will need to design for worst case expulsion velocity and worst case total suppressant quantity to ensure sufficient suppressant to extinguish a fire.

A test series was also conducted to evaluate the effectiveness of HFC-227ea with common spacecraft materials and configurations. The testing demonstrated that HFC-227ea can be a successful extinguishment media for flammable material configurations. However, rather than the terrestrial reported extinguishment threshold of 6.8%, testing showed HFC-227ea to be effective in the above ~11% range. Additionally, the extinguishment mechanism is less effective against materials such as cotton and that exasperated burn rates, as high as double, should be expected to be encountered when HFC-227ea media is introduced prior to reaching extinguishment limits.

While the terrestrial PFEs tested in this effort are predicted to functionally discharge suppressant in microgravity, testing shows that neither the quantity discharged in microgravity, nor the effectiveness of the suppressant with spacecraft materials, matches the 1-G capabilities. Accordingly, space vehicles intending to use terrestrial PFEs in microgravity must account for the decreased suppressant expulsion rates, the unavoidable suppressant hold-up, and the decreased effectiveness when sizing their PFEs for targeted vehicle volumes. Further, hydrofluorocarbons should only be used in spacecraft when extinguishment concentrations can be achieved rapidly and for sufficient dwell time such that the suppressant does not exacerbate the fire.

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