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RÉPONSE

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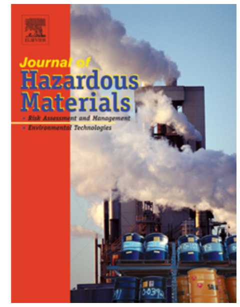

Title: Modeling the Release, Spreading, and Burning of LNG, LPG, and Gasoline on Water

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Modeling the Release, Spreading, and Burning of LNG, LPG, and Gasoline on Water

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Abstract

Current interest in the shipment of liquefied natural gas (LNG) has renewed the debate about the safety of shipping large volumes of flammable fuels. The size of a spreading pool following a release of LNG from an LNG tank ship has been the subject of numerous papers and studies dating back to the mid-1970s. Several papers have presented idealized views of how the LNG would be released and spread across a quiescent water surface. There is a considerable amount of publicly available material describing these idealized releases, but little discussion of how other flammable fuels would behave if released from similar sized ships. The purpose of this paper is to determine the whether the models currently available from the United States Federal Energy Regulatory Commission (FERC) can be used to simulate the release, spreading, vaporization, and pool fire impacts for materials other than LNG, and if so, identify which material-specific parameters are required.

The review of the basic equations and principles in FERC's LNG release, spreading, and burning models did not reveal a critical fault that would prevent their use in evaluating the

consequences of other flammable fluid releases. With the correct physical data, the models can be used with the same level of confidence for materials such as LPG and gasoline as they are for LNG.

Keywords: LNG, modeling, spills on water, fire radiation

1.0 Introduction

Current interest in the shipment of liquefied natural gas (LNG) has renewed the debate about the safety of shipping large volumes of flammable fuels. The size of a spreading pool of LNG following a release from an LNG tank ship has been the subject of numerous papers and studies dating back to the mid-1970s [1, 2, 3, 4]. In 2004, the Federal Energy Regulatory Commission (FERC) contracted with ABS Consulting to identify appropriate consequence analysis methods for estimating flammable vapor and thermal radiation hazard distances for potential releases of LNG from tank ships during transit and while at berth.

The results of the study were initially published on May 13, 2004. After review by FERC staff and public comments, a revised consequence analysis methodology was issued by FERC on June 18, 2004. On June 29, 2004, the NOTICE OF AVAILABILITY OF DETAILED COMPUTATIONS FOR THE CONSEQUENCE ASSESSMENT METHODS FOR INCIDENTS INVOLVING RELEASES FROM LIQUEFIED NATURAL GAS CARRIERS, Docket No. AD04-6-000, was issued [5]. Since June 29, 2004, these computational methods have become the "de facto" standard for evaluating the release, spreading, and pool fire hazards presented by the marine transport of LNG in the United States.

There has been much public comment regarding the models recommended by the study. In general, the models suffer from a lack of large-scale validation. This is not an uncommon problem for any of the computational methods that can be used to perform consequence analysis for LNG releases. To date, no large-scale (i.e., larger than 35 m diameter pools) LNG release, pool spreading, dispersion, or fire testing experiments have been performed.

LNG has been transported by ship for the past forty years. During this same time period, shipments of other flammable fuels, such as liquefied petroleum gas (LPG), crude oil, gasoline, and diesel fuel, have also been made, and with much higher frequencies. In many cases, the ships that transport these flammable fuels are as large or larger than LNG ships currently in use (18,000 to 145,000 m^3). As in the case of large-scale LNG experiments on water, there have not been any large-scale experiments involving LPG, gasoline, or other flammable fuels on water.

While reviewing the liquid release, spreading, and burning models incorporated into the FERC LNG model, it is worth investigating whether this model can be modified so that it can be used to predict the consequences associated with releases of other flammable fuels on water.

2.0 Brief Discussion of the FERC Consequence Analysis Models

The FERC consequence analysis models compute the rate of release from a hole in a containment vessel, the subsequent spreading of the released liquid, the evaporation of the liquid, and, if the liquid is ignited, fire radiation resulting from the flame column. The model writes out a time-vapor rate-radius file suitable for use by the DEGADIS vapor dispersion program, but the FERC model does not link to the DEGADIS program.

2.1 Release Rate

The rate of release of LNG from a containment vessel is computed using the following orifice formula.

$$Q = C_d \, \rho_l \, A_h \sqrt{2gH} \qquad (1)$$

$$\begin{aligned} where: \quad & Q && = mass\ flow\ rate, kg/s \\ & C_d && = discharge\ coefficient, assumed\ to\ be\ 0.65 \\ & \rho_l && = density\ of\ LNG, kg/m^3 \\ & A_h && = area\ of\ hole, m^2 \\ & g && = gravitational\ constant, 9.81\ m/s^2 \\ & H && = liquid\ height\ above\ hole, m \end{aligned}$$

Equation (1) implies a circular smooth-edged hole and a non-flashing liquid at the orifice. While it can be argued that a hull breach in a marine LNG carrier would likely not be circular or smooth-edged, the actual shape of the breach cannot be definitively determined beforehand. Thus, the circular smooth-edged hole is a reasonable starting point for flow calculations.

A more serious limitation to Equation (1) is the neglection of the ullage pressure in the tank. A typical ullage pressure of 0.14 kg/cm^2 (2 psi) can increase the effective liquid height by 2.5 m.

2.2 Liquid Spreading

The spreading of LNG on a water surface follows the technique developed by Webber [6]. The governing equation is:

$$\partial^2 r / \partial t^2 \quad = \left[4\, g_r\, \Phi\, h / r\right] - C_f \tag{2}$$

$$
\begin{aligned}
where: \quad & r && = pool\ radius, m \\
& t && = time, s \\
& g_r && = g\left(\rho_w - \rho_l\right) / \rho_w, m/s^2 \\
& \rho_w && = density\ of\ liquid\ substrate, kg/m^3 \\
& \Phi && = coefficient\ that\ is\ a\ function\ of\ h_f / h \\
& h_f && = pool\ height\ at\ leading\ edge, m \\
& h && = mean\ pool\ height, m \\
& C_f && = frictional\ resistance\ force, m/s^2
\end{aligned}
$$

As originally proposed, the frictional resistance term, C_f, was for a liquid in direct contact with the substrate. This assumption was questioned since it is known that LNG forms a thin vapor film when in contact with a warm surface. The frictional resistance term was eventually changed in the final ABS report (June, 2004) to account for the formation of a low friction vapor film.

Solution of Equation (2) involves an iterative approach, adding and subtracting LNG from the pool at each time step due to the spillage and vaporization that is taking place. As currently implemented, Equation (2) is useful only for cryogens that form a vapor film. For liquids that do not form vapor films, the original development by Webber [6] can be used.

2.3 Liquid Vaporization on Open Water

Liquid is removed from the LNG pool by vaporization. Vaporization occurs due to two mechanisms: 1) heat transfer from the substrate surface to the pool and 2) heat transfer from the flame to the pool if the pool is ignited.

Several theoretical models for computing the heat transfer from a large water surface are explored in the ABS report. However, the FERC model assumes a constant value of heat transfer for LNG based on whether or not the pool is burning. For a non-burning LNG pool, a constant heat transfer flux of 85 kW/m^2 (0.167 kg/m^2-s) is used. For a burning LNG pool, a constant heat transfer flux of 143 kW/m^2 (0.282 kg/m^2-s) is used. The burning vaporization flux includes heat transfer from the liquid substrate and from the flame. These values were chosen based on a review of available information.

2.4 Fire Radiation

The FERC model computes fire radiation from a burning LNG pool using a solid flame model. Radiation from the flame to a receptor can be computed using the following relationship.

$$q = \tau F E \tag{3}$$

$$\begin{aligned} where: \quad & q && = incident\ radiant\ flux, kW/m^2 \\ & \tau && = atmospheric\ transmissivity, the\ fraction\ of\ energy \\ & && \quad leaving\ the\ flame\ that\ reaches\ the\ receptor \\ & F && = view\ factor\ between\ flame\ and\ receptor \\ & E && = surface\ emissive\ power\ of\ flame, kW/m^2 \end{aligned}$$

For LNG, *E* is defined as 265 kW/m^2 in the model. The atmospheric transmissivity, τ, is computed with:

$$\tau = 2.02\left[P_{water}/x\right]^{-0.09} \tag{4}$$

$$\begin{aligned} where: \quad & P_{water} && = partial\ pressure\ of\ water\ vapor\ in\ air, pascals \\ & x && = line\ of\ sight\ distance\ from\ point\ on\ flame\ to\ receptor, m \end{aligned}$$

The view factor, *F*, is found using the following formula.

$$F = \iint_S \left[\cos(\beta_1) \cos(\beta_2) / \pi d^2 \right] dA_1 \quad (5)$$

$$\begin{aligned} where: \quad & \beta_1 \ and \ \beta_2 && = angles\ between\ line\ joining\ flame\ and\ receptor\ and \\ & && \ \ \ line\ normal\ to\ flame\ surface\ or\ receptor\ surface \\ & d && = distance\ between\ flame\ surface\ element\ and\ receptor, m \\ & dA_1 && = small\ area\ on\ flame\ surface, m^2 \end{aligned}$$

The integral found in Equation (5) is evaluated over the entire surface of the flame. The physical dimensions of the flame (flame length, clear length of flame, flame tilt angle, etc.) are computed using the methods developed by Rew [7] and AIChE (2000) [8] as outlined in the revised consequence analysis methodology issued by FERC on June 18, 2004.

The methodology suffers from a lack of validation for large LNG fires. The largest fire for which experimental data is available is approximately 35 m in diameter [9]. Further, the algorithm for determining the flame length predicts that the length increases at a rate proportional to $D^{0.74}$.

2.5 Information Required to Predict the Release, Spread, and Burning Behavior of Liquids Using the FERC Models.

Using published information regarding the FERC models, Table 2.1 summarizes the material properties required for the use of these models.

Table 2.1

Specific Material Information Required for FERC Models

Property	Description	Units	Used to Compute
CH	carbon to hydrogen ratio	none	fire radiation
E_s	flame surface flux	kW/m^2	fire radiation
h_{fg}	liquid heat of vaporization	J/kg	liquid spreading
k_v	thermal conductivity of vapor	W/(m·K)	liquid spreading
m_b	burning vaporization flux	$kg/(m^2{\cdot}s)$	liquid spreading, fire radiation
m_w	molecular weight	kg/kg-mol	liquid spreading, fire radiation
δ	vapor film thickness for cryogenic liquids	m	liquid spreading
μ_l	viscosity of liquid	Pa·s	liquid spreading
μ_v	viscosity of vapor	Pa·s	liquid spreading
ρ_v	density of vapor	kg/m^3	fire radiation
ρ_l	density of liquid	kg/m^3	release rate, liquid spreading
σ	liquid surface tension	N/m	liquid spreading

The FERC models were used to calculate the hazard zones associated with releases of LNG (as CH_4), LPG (as C_3H_8), and gasoline (as *n*-Octane, C_8H_{18}). Since the compositions of the three selected materials vary from source to source, pure component properties were used in the calculations. Properties for these three materials are presented in Table 2.2.

Table 2.2
Material Properties Used in Calculations

Property	Value			Units
	CH_4	C_3H_8	n-Octane	
CH	0.250	0.375	0.444	none
E_s	265.0	195.0	115.0	kW/m^2
h_{fg}	509,332.	425,770.	301,260.	J/kg
k_v	0.0127	0.0140	0.0113	W/(m·K)
m_b	0.282	0.142	0.074	$kg/(m^2 \cdot s)$
m_w	16.0	44.1	114.2	kg/kg-mol
δ	6.3e-05	6.3e-05* 3.2e-05* 0.0*	0.0†	m
μ_l	1.2e-04	2.0e-04	5.5e-04	Pa·s
μ_v	4.4e-06	6.4e-06	6.8e-06	Pa·s
ρ_v	1.75	2.43	5.43	kg/m^3
ρ_l	422.5	570.0	688.3	kg/m^3
σ	0.013	0.015	0.022	N/m

* *range of vapor film thickness used to evaluate the effect of this variable.*

† *For liquids with film thickness of 0.0 m, the initial ABS/FERC report (May 13, 2004) spreading model was used in this evaluation.*

Material properties were determined at one atmosphere pressure and the normal boiling point of each material. *n*-Octane properties were determined at one atmosphere pressure and 291.4 K (65°F). Thermal conductivities were evaluated at the average temperature between the normal boiling point and the assumed seawater temperature of 291.4 K (65°F). CH_4 (LNG) material properties were the same as used by FERC.

3.0 Results

Calculations were made using the FERC models summarized in Section 2 for two release scenarios. For each release scenario, the material properties listed in Table 2.2 were used. Releases were assumed to occur over seawater at 291.4 K (65°F). Pool spreading was assumed to occur in a radial direction without obstacles (i.e., circular pools).

3.1 Scenario 1 - Equal Release Volumes

In this scenario, the liquid is assumed to be spilling from a cargo tank containing 25,000 m^3 of liquid, of which 12,500 m^3 of the subject liquid is above the waterline. In all cases, the liquid pool was assumed to ignite upon release. The liquid head above the waterline was assumed to be 13 m. A 1-m hole at the waterline was assumed. For the C_3H_8 releases, vapor film thicknesses of 6.3×10^{-5}, 3.2×10^{-5}, and 0.0 m were used to demonstrate the model sensitivity to this parameter. Table 3.1 summarizes the results of the computations. Times, radii, and distances in all tables are rounded to the nearest 5 (s, m, m).

Figure 3.1 shows the mass release rate for each material. As would be expected for the case of equal volumes and equal liquid heads, the mass rate of release of gasoline, the highest density fluid, is greater than for LPG or LNG. The underlying assumption that the flammable material is ignited upon release results in the radius of the burning pool varying with time, as shown in Figure 3.2. The burning gasoline pool grows to a larger maximum diameter than the LNG and LPG pools. This is primarily due to the lower vaporization rate of the gasoline when compared to LNG and LPG. For equal volume releases, the gasoline pool grows to a pool with twice the diameter of the LNG pool.

As can be seen from the results in Table 3.1 and Figure 3.3, the choice of the LPG vapor film thickness does not significantly influence the results.

Figure 3.4 shows the radiant thermal flux vs. distance for each material. These calculations were made at each pool's maximum radius. Reviewing Figures 3.2 and 3.4 and the model inputs show that the combination of larger pool radius, lower flame height, and lower radiant surface flux for gasoline results in a similar radiant impact as the LNG and LPG pool fires with their smaller pool radii, taller flame heights, and higher radiant surface fluxes. Using 5 kW/m^2 as a common radiant impact limit, Table 3.1 shows that the gasoline and LNG radiant impacts extend 620 meters from the center of the pool, while the LPG impacts are slightly smaller.

This analysis shows that for equal volumes of these flammable materials, the impacts from an expanding burning pool are nearly identical.

3.2 Representative Cargo Releases

This scenario is based on tank ship compartments that are more representative of actual tank ships in use today: a 125,000 m^3 LNG ship with 25,000 m^3 cargo tanks for LNG (of which 12,500 m^3 of the liquid is above the waterline), an 80,000 m^3 insulated LPG ship with 20,000 m^3 cargo tanks for LPG (of which 7,415 m^3 of the liquid is above the waterline), and an 85,000 m^3 Panamax refined products tank ship with 8,000 m^3 cargo tanks for gasoline (of which 2,460 m^3 of the liquid is above the waterline). Due to differing liquid densities, these assumptions result in an initial liquid height above the hole of 13 m for LNG, 9.6 m for LPG, and 8 m for gasoline. For each cargo tank, a 1-m hole at the waterline was assumed. For the C_3H_8 releases, a vapor film thicknesses of 3.2×10^{-5} m was used. Table 3.2 summarizes the results of the computations. Times, radii, and distances in all tables are rounded to nearest 5 (s, m, m).

The trade offs apparent in the equal volume releases are present in the representative cargo releases. A review of Table 3.2 and Figure 3.5 shows the radius of the LNG pool is smaller than the radius of the gasoline pool, even though the total volume of LNG released is five times larger. This is partly due to the nature of the spreading model. The gasoline pool continues to spread and burn until the fuel is exhausted. The LNG and LPG pools spread and burn in a similar manner, but the film thickness algorithm in the FERC model allows the pool to shrink instead of breaking up as discussed by Otterman [2].

A review of Table 3.2 and Figure 3.6 shows that a 2,460 m^3 release of gasoline and a 12,500 m^3 release of LNG result in similar radiant impacts for the higher flux levels. When reviewing the results for the lower (i.e., 5 kW/m^2) radiant flux level, the impacts from the LNG fire extend further. This is primarily due to the taller flame height associated with the LNG fire.

4.0 Summary

A review of the basic equations and principles in FERC's LNG release, spreading, and burning models did not reveal a critical fault that would prevent using them to evaluate the consequences of other flammable fluid releases. With the correct physical data, the models can be used with the same level of confidence for materials such as LPG and gasoline as they are for LNG. The limitations identified in the FERC model also apply to the other materials.

The most important result of this review is the identification of the behavior of flammable fluids under similar circumstances using the same modeling tools. The variation in spreading rates, vaporization rates, and flame heights for three commonly shipped flammable materials show that the more volatile material, LNG, will not produce a significantly larger radiant impact than a smaller release of a lower volatility material such as gasoline when releases from typical cargo containers under similar conditions are evaluated. A more detailed study considering other factors including hole size, cargo composition and inventory may yield different results.

Table 3.1
Equal Release Volume Results for 1-Meter Diameter Hole

Material	Film Thick. (m)	Total Volume Released (m^3)	Time to Empty (s)	Time to Evaporate All Liquid (s)	Max. Radius (m)	Distance in meters to Radiant Flux in kW/m^2 at a Wind Speed of 9 m/s		
						30	9	5
LNG (CH_4)	$6.3x10^{-5}$	12,500	3,070	3,070	70	300	495	620
LPG (C_3H_8)	$6.3x10^{-5}$	12,500	3,070	3,085	100	275	445	555
	$3.2x10^{-5}$	12,500	3,070	3,085	105	280	455	560
	0.0	12,500	3,070	3,085	115	305	490	605
Gasoline (C_8H_{18})	0.0	12,500	3,070	3,135	155	375	530	620

Table 3.2
Representative Cargo Compartment Results for 1-Meter Diameter Hole

Material	Film Thick. (m)	Total Volume Released (m^3)	Time to Empty (s)	Time to Evaporate All Liquid (s)	Max. Radius (m)	Distance in meters to Radiant Flux in kW/m^2 at a Wind Speed of 9 m/s		
						30	9	5
LNG (CH_4)	$6.3x10^{-5}$	12,500	3,070	3,070	70	300	495	620
LPG (C_3H_8)	$3.2x10^{-5}$	7,415	2,115	2,130	95	260	420	520
Gasoline (C_8H_{18})	0.0	2,460	770	935	110	280	400	465

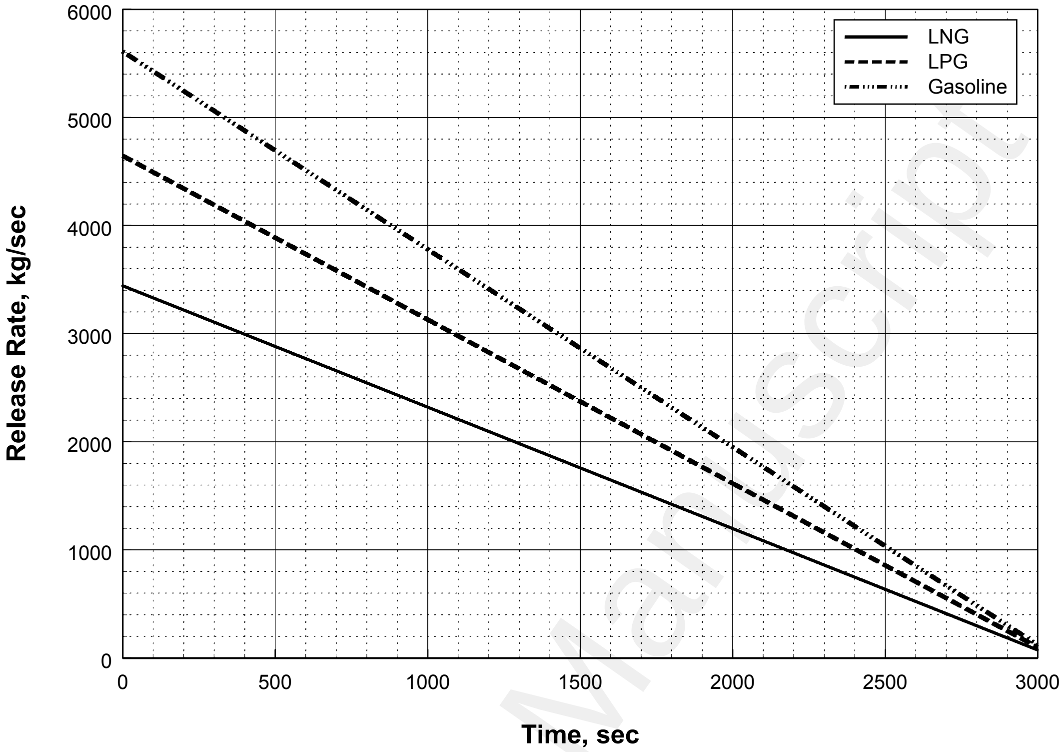

Figure 3.1 Equal Volume Releases
Release Rate vs. Time for 1-m Diameter Hole

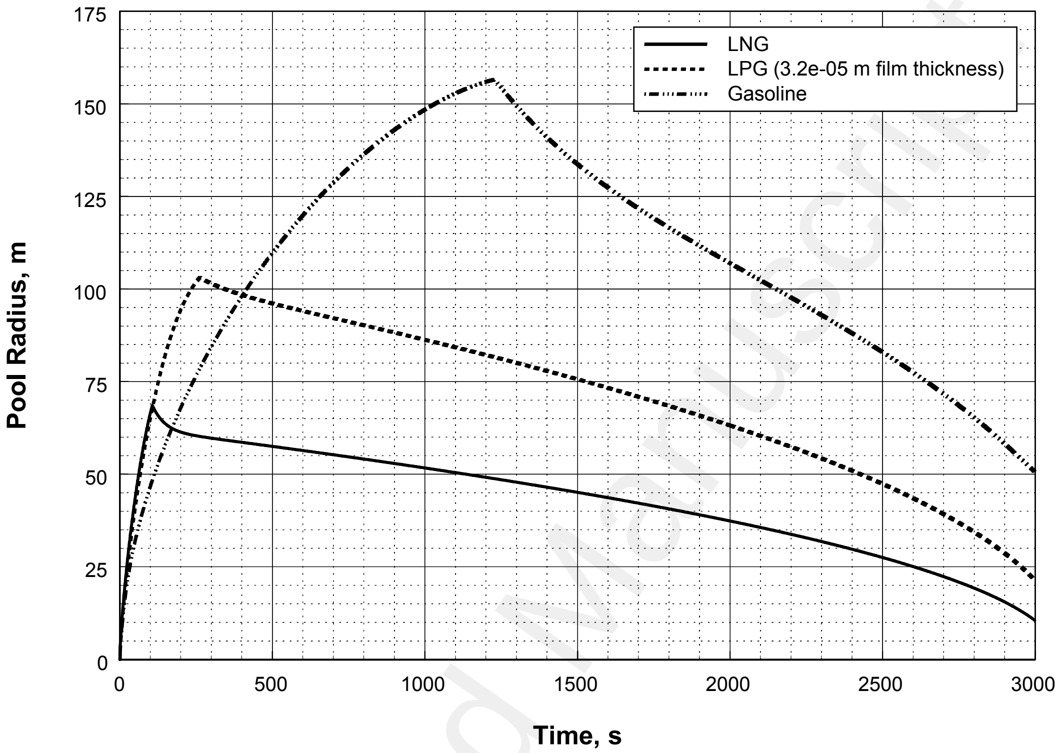

Figure 3.2 Equal Volume Releases
Pool Radius vs. Time for 1-m Diameter Hole

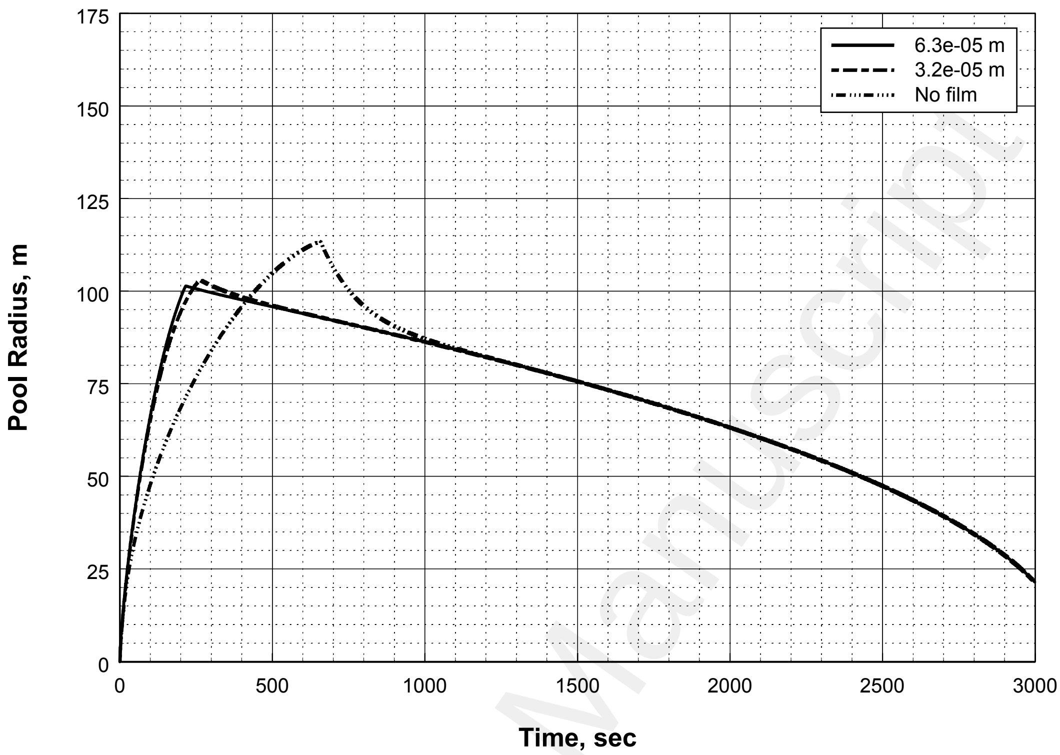

Figure 3.3 Equal Volume Releases
Pool Diameter vs. Time for LPG at Different Film Thicknesses

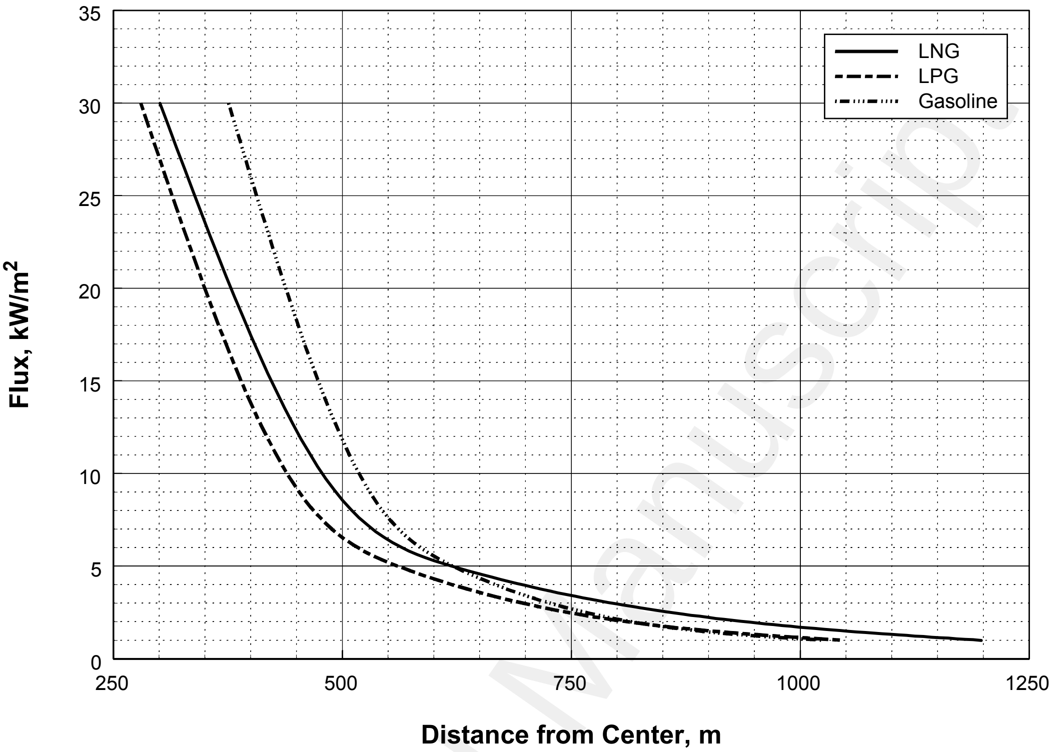

Figure 3.4 Equal Volume Releases
Radiant Flux vs. Distance for 1-m Diameter Hole

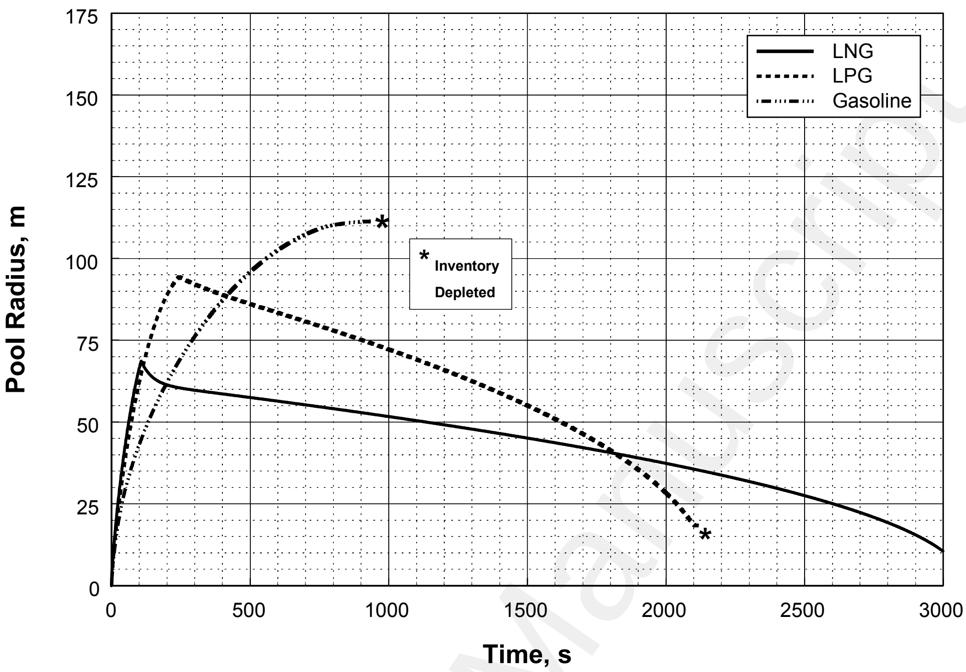

Figure 3.5 Representative Cargo Volumes
Pool Radius vs. Time for 1-m Diameter Hole

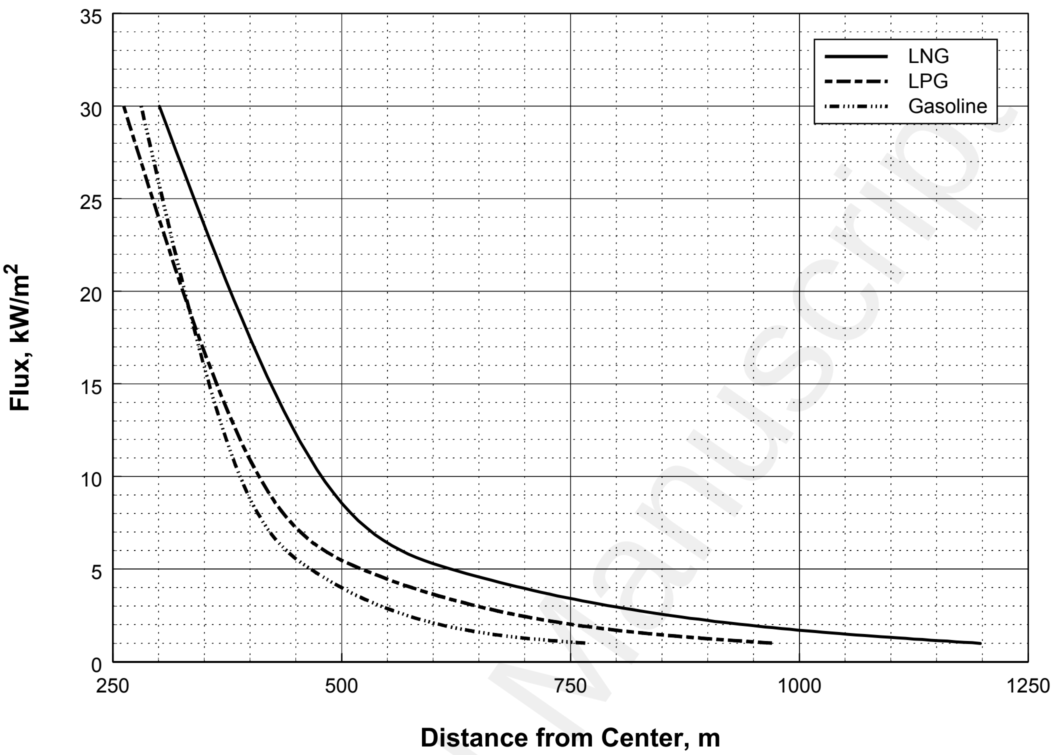

Figure 3.6 Representative Cargo Volumes
Radiant Flux vs. Distance for 1-m Diameter Hole

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