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Drop Formation and Evaporation of JP-4 Fuel Jettisoned from Aircraft

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The occasional jettison of unburned fuel from aircraft has raised the concern of environmentalists as to possible change in atmospheric composition or damage to crops. To address this concern, it is necessary to know under what conditions unburned fuel will reach the ground and what fraction of the fuel is vaporized. This information can be calculated once the initial drop size created during the fuel venting is known. To determine the actual drop sizes formed, an experimental program was conducted. It consisted of flying a sampling aircraft directly through a fuel dump at selected altitudes to measure fuel drop size and number distributions. The measurement results of the sampling, fuel dump wake size, and hydrocarbon vapor content are presented. A multicomponent fuel drop model is used to correct the observed drop size distribution. For the KC-135 aircraft fuel venting procedures, the median drop diameter formed is 270 μm. It is determined that for surface temperatures above 0°C, more than 98% of the fuel jettisoned 1500 m or higher will evaporate before reaching the ground. Ground contamination can be avoided, eliminating any potential environmental damage.

Nomenclature

b	= wing span
d	= fuel drop diameter
K	= diffusivity
t	= time
U	= aircraft speed
V	= relative speed of drop
v	= speed of jettisoned fuel
W	= aircraft weight
W_e	= Weber number
Z	= altitude
ρ	= atmospheric density
σ	= surface tension of fuel
σ_y, σ_z	= standard deviations of vapor distribution
τ	= characteristic wake time
ν	= kinematic viscosity

I. Introduction

AVIATION fuel, when dumped from a jet aircraft, readily breaks up into small droplets, vaporizes, and soon becomes a minute constituent of the atmosphere. At the expected large dilution that is likely to occur, no environmental harm is expected. Nevertheless, quantitative knowledge of the various processes has not been thoroughly examined. The study here has been undertaken to investigate in a detailed manner the physical processes following the dumping of the fuel from a jet aircraft. The purpose is to define the initial fuel drop number and mass distribution with size, the fraction of fuel vaporized, and the fall rate of the fuel droplets. The environmental assessment of the dumped fuel can then be made using chemical reaction models to evaluate chemical changes in the atmosphere and droplet evaporation models to determine how much can reach the ground surface from a given altitude.

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The experimental investigation was conducted in December 1976. A sampling aircraft equipped with droplet spectrometers and hydrocarbon analyzer was flown directly into fuel vented from a KC-135 aircraft. Direct measurements of the fuel drop size distribution and density were obtained and the fall rates measured. These measurements were successfully conducted and represent unique data never before obtained in flight.

The atomization process of a liquid jet consists of the airstream stripping away filaments of liquid which subsequently breakup into droplets. The maximum-size drop that can remain stable in an airstream is dependent upon the ratio of dynamic pressure force to the surface tension force, known as the Weber number. The studies of Hinze,[1] Volynski,[2] and Lane and Green[3] determined the maximum stable drop size Weber[15] number between 5.3 and 10. The critical value depends upon the way in which the relative velocity varies with time, and it has a higher value (about 10) for the case of free falling drops.[3] The maximum stable drop size for drops suddenly exposed to the aircraft speed is estimated by taking $W_e = 5.3$

$$d_{\max} = \frac{W_{e_{\max}} \sigma}{V^2 \rho} = \frac{111.0}{V^2 \rho} \tag{1}$$

where the JP-4 fuel surface tension is taken as $\sigma = 21$ dyn/cm^2 (see Ref. 4). At the KC-135 flight speed of 170 m/s, the maximum drop size at 3730 m is calculated to be $d_{\max} = 4.7$ μm.

Most of the fuel dump cannot be atomized to such small particle size because the entire 10-cm fuel jet core does not encounter the full airstream velocity instantaneously. Instead, the fuel jet is broken up into large filaments by the velocity. By the time the fuel filaments are broken up into drops, the relative airstream velocity has been considerably reduced. It is impossible to estimate precisely the relative velocity at the point of drop formation. In fact, an entire spectrum of drop sizes is expected ranging from small, light-scattering particles to some of maximum size. This range of particle sizes occurs because the region of droplet formation spreads from the outer edge of the initial jet to the centerline as the relative velocity decreases downstream. Eventually, the motion of the fuel droplets is governed entirely by the force due to gravity.

The drops then fall in the quiescent atmosphere and reach a terminal velocity in a matter of seconds. Under these conditions, it is possible to estimate a maximum drop size as determined by their terminal velocity. For free falling drops, Lane and Green[3] suggest the critical Weber number is 10, and consequently, the maximum stable drop diameter would be 2250, 2300, and 2150 μm at 1580-, 3730-, and 6250-m alt, respectively, for the KC-135 aircraft. Thus, it can be expected that drop sizes formed in venting from an aircraft will initially range between some 5 and 2500 μm.

The earliest measurement of drop size from jettisoned liquids was performed by Merrington and Richardson.[5] They studied the breakup by dropping various liquids from a tower and from a low flying aircraft. In both instances, they determined the drop size distribution by measuring the drop impressions left on "blotter" paper and by applying evaporation corrections. Using nozzle diameters between 0.076 and 1.67 cm, they found the mass average drop diameter to vary inversely with the relative air velocity. Merrington and Richardson derived an expression, using liquid viscosities, as

$$V\bar{d} = 500\,\nu^{1/5} \tag{2}$$

where V is the velocity between the airstream and the jet in cm/s and $\bar{d}$, in cm, is the mean drop size taken to be that corresponding to 50% of the mass discharged. Merrington and Richardson were unable to determine any drop size dependence on the nozzle diameter.

The next study of liquid jet breakup was conducted by Cross and Picknett[6] to investigate the possibility of pollution from jettisoned aviation fuel. Cross and Picknett used a small jet flying at a speed of 120 m/s and 15 m off the ground to jettison the fuel at right angles to the airstream. They determined the mass size distribution from four separate flights over filter paper laid out on the ground. They found a mean diameter for AVTUR fuel (JP-1) of 215 and 265 μm on each of three similar tests. Cross and Picknett estimate the mean diameter to be 275 μm if they had used a straight exit nozzle rather than the right angle exit nozzle. Cross and Picknett were able to account for only 55% of the total mass vented. They assumed that small drops ($d<40$ μm) drifted away. Cross and Picknett assumed the drops would not evaporate in falling 15 m. Using the model described later, we can estimate the evaporation which could occur under such conditions. Since the study was performed in August, we will assume a surface temperature of 25°C. Then, following Lowell's suggestion[7] that initial JP-1 evaporation rates are equivalent to the evaporation of JP-4 at a temperature 20°C lower, we can run the model for JP-4 at 5°C in order to simulate JP-1 at 25°C. Under the free fall conditions, a 350 μm drop would fall 15 m in 15 s, evaporate 57% of its mass, and would be reduced to about the observed 260 μm when it hit the ground. It would appear that if Cross and Picknett had included evaporation effects they might have accounted for all the fuel.

The existing data of Merrington and Richardson and Cross and Picknett (corrected for evaporation) predict a mean drop diameter of 1000 and 350 μm, respectively. The different diameters cannot be scaled using Eq. (2), and one is left with no reliable means of estimating the initial median drop diameter occurring during a fuel venting from modern jet transport aircraft. New experiments were conducted to provide the necessary information on the initial drop sizes formed during a fuel vent. The following describes these experiments.

II. In-Flight Measurements and Analysis

The Navaho sampling aircraft was provided by Meterorology Research, Inc., under Air Force contract to conduct the measurements and report the fuel droplet size and number distribution. A two-volume detailed data report[8] describes the measured fuel dump droplet characteristics. The Navaho aircraft was equipped with instruments normally used in cloud physics, weather modification, and air quality assessments. These instruments[9] consist of three particle spectrometers capable of measuring particles in size ranges of 2-30 μm, 20-300 μm, and 300-4500 μm. A foil impactor was flown to register impact impressions of drops having a diameter greater than 250 μm. Instruments specifically added for this research consisted of a hydrocarbon analyzer sensitive between 0.1 and 1,000 ppm and an integrating Nephelometer to provide large volume measurements of small particles.

The fuel-venting experiment was conducted over the Edwards AFB test range. The fuel was vented from a KC-135 tanker aircraft which was flown at 1580, 3730, and 6250 m into the prevailing wind to minimize lateral drift of the fuel dump. The fuel vent was visible to the eye initially for a few minutes as a white, trailing wake. Under favorable viewing directions, the fuel cloud could be seen up to 10 min after the vent. The visible cloud represents only the small droplet size particles. Larger particles which fall out of the visible cloud cannot be seen. Detection of the larger drops could only be attempted by guiding the sampling aircraft into suspected regions using real-time radar tracking of the tanker and sampling aircraft. The sampling aircraft was vectored back and forth over the dump location at various altitudes to gather information. The flight and fuel vent parameters of the KC-135 tanker are listed in Table 1.

The results of the measurements of the drops vented from the KC-135 aircraft are presented in detail by Good et al.[10] A sample of the repeated measurements following a single fuel vent are illustrated in Fig. 1. The fuel was vented at 3730-m alt. The sampling aircraft flew up and down the short trail with its position recorded by range radar. The altitude of the sampling aircraft varied during each pass in an attempt to keep up with the descending drops. The actual altitude of the sampling aircraft is noted in the figures as the distance ΔZ below the fuel vent altitude. A continuous drop distribution is obtained with two instruments; the aerosol particle spectrometer (APS) recorded drops in the 2-30 μm range, and the cloud particle spectrometer (CPS) recorded drops in the range of 20-300 μm. The precipitation particle spectrometer (300-4500 μm), in this particular sortie, did not detect large drops. A collection of observations on 1580-m fuel dumps is shown in Fig. 2, illustrating the variability that was observed. The variation is attributed to sampling at different height levels within the fuel dump volume.

The significant difference between these and previous experiments is the in-flight sampling. The previous experiments had the aircraft fly within 15 m of the ground. The fuel was allowed to fall to the ground in the presence of the aircraft ground effect created by wing tip vortices. In those cases, the elapsed time between dump and ground contact was on the order of 10 s. This experiment was able to make the first sampling after about 60 s. This added time permits considerably more evaporation of the drops to occur before the initial sampling. The numerical calculation using an evaporation model indicates that an initial 300-μm-diam drop, at 1580-m alt, will evaporate to about 170-μm diam during the first minute. In this time, the drop will lose some 80% of its original mass through evaporation.

Table 1 KC-135 flight and fuel vent parameters

Altitude, m	Airspeed, m/s
1580	154
3730	170
6250	180
Nozzle diameter:	10.1 cm
JP-4 dump rate:	56 kg/s or 330 g/m
Nominal dump cross section at 90 s determined from photographs: 100 m × 100 m	

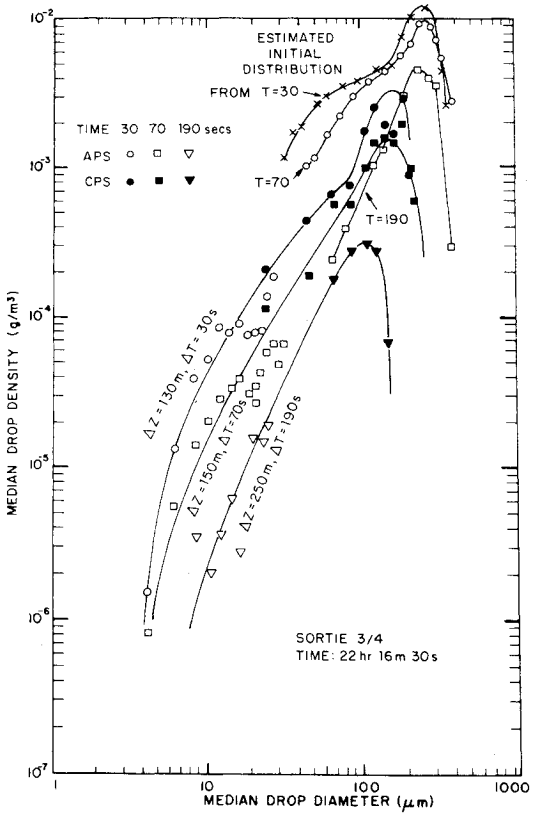

Fig. 1 JP-4 drop density measurement by sampling aircraft penetrating the fuel dumped by a KC-135 aircraft at 3730 m. The top three curves represent the original drop distribution estimated from the measured curves using the evaporation model.

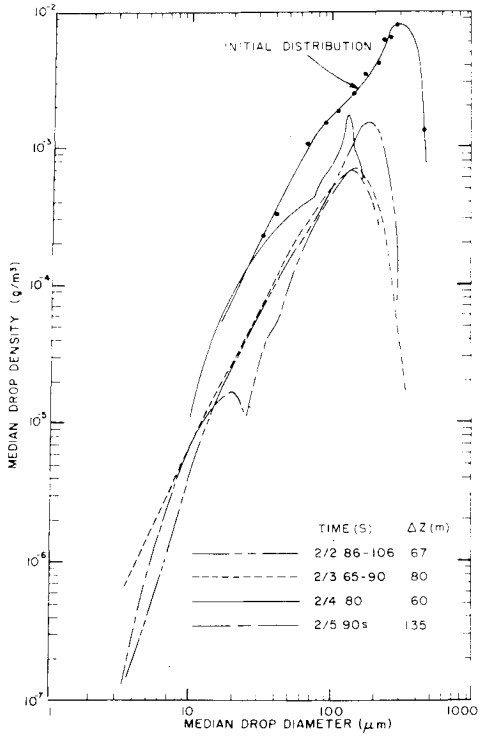

Fig. 2 JP-4 drop density measured during the first sampling pass of five fuel dumps from 1580 m. The original distribution is derived from a composite model of the measurements with corrections for evaporation.

III. Droplet Evaporation Modeling

The calculation of the free fall and evaporation of fuel droplets is based on the work of Lowell.[7,11] Lowell's method has been refined and extended chiefly by the incorporation of experimental vaporization data provided by Dawbarn,[4] and by the use of a more detailed fuel composition. The data provided by Dawbarn[4] included measurement of the drag coefficients and evaporization rates of JP-4 fuel droplets as well as the physical properties of JP-4 as a function of temperature. Data on the composition of JP-4 provided by the Air Force Aero-Propulsion Laboratory were used to prepare a theoretical 33-component "synthetic JP-4" mixture.[14] The calculated physical properties of this mixture (density, average carbon number, and Reid vapor pressure) agree well with typical analyses of JP-4. Each component in the synthetic mixture represents a class of compounds in real JP-4. Lowell used ten equal volume distillate fractions to represent JP-4; the more detailed composition here allows modeling of the droplet to continue until virtually all (99.9%) of the mass is gone.

Essentially, the calculation considers a given droplet's fall as a series of small time intervals. The distance of fall during each interval is calculated assuming the droplet is falling at the terminal velocity for its current diameter and altitude. Loss of mass through evaporation is calculated assuming Raoult's law; that is, each compound evaporates independently. An energy balance routine[12] adjusts the droplet temperature to allow for evaporative cooling. The new droplet composition, mass, and altitude are used as initial conditions for the next interval. This stepwise approximation continues until the droplets impact on the ground or lose 99.9% of their initial mass.

The initial conditions which must be known are the droplet's original composition and diameter, surface elevation and temperature, and the aircraft's air speed and altitude. The initial droplet temperature is then taken as the corresponding stagnation temperature, assuming equilibration of the fuel tanks with the skin of the aircraft. In the early intervals, the droplet is allowed to cool through evaporation until an energy balance is achieved. At the beginning of each interval, the droplet's current mass, composition, and altitude are known. The local air temperature is derived at the droplet altitude using the surface temperature and the standard lapse rate. Atmospheric pressure density and viscosity are calculated as recommended in the 1976 *U.S. Standard Atmosphere.*[13]

The model reports the droplet's status at the end of each time interval or at selected periods of time. Output includes the elapsed time since release; the droplet altitude, velocity, diameter, and fraction of initial mass remaining; and the fractional mass of each component. A complete description of the model is presented by Clewell.[14]

The numerical results for one altitude are plotted in Fig. 3 in terms of the observational parameters: the observed diameter, and the observing time taken as elapsed time from the fuel vent until the observation. Fig. 4 presents the estimated percentage of the initial drop mass remaining at the observing time. Fig. 3 and similar curves at other altitudes (see Ref. 10) were used to correct the observed drop diameter for evaporation to estimate the initial drop diameter. Once the original drop diameter is determined, the percentage of mass remaining at the observation time is determined from Fig. 4 for the 3730-m data and similar curves for the data at other altitudes. The experimental initial drop density is then estimated by correcting the observed drop density by the ratio of original mass to mass remaining at the observation time. The calculated original drop distributions are shown in Figs. 1 and 2.

IV. Results

The original drop spectrums for all altitudes are summarized together in Fig. 5. No clear altitude distinction can be noted. It would appear that a maximum drop density of 0.01 g/m³ exists with drops of diameter 200-300 μm. A model

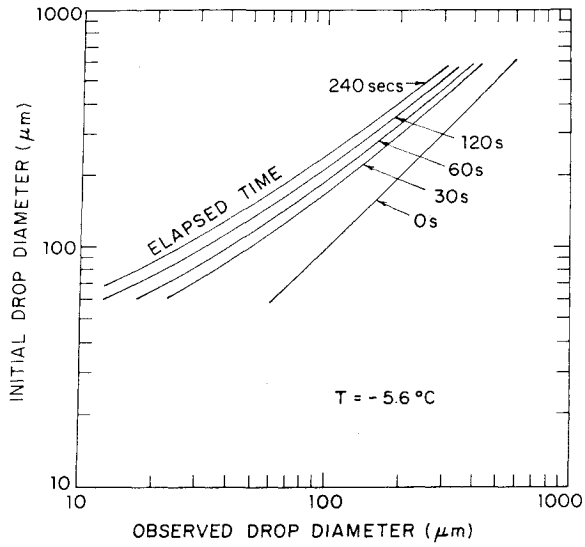

Fig. 3 Original drop diameter in terms of drop diameter to be observed falling from 3730-m alt.

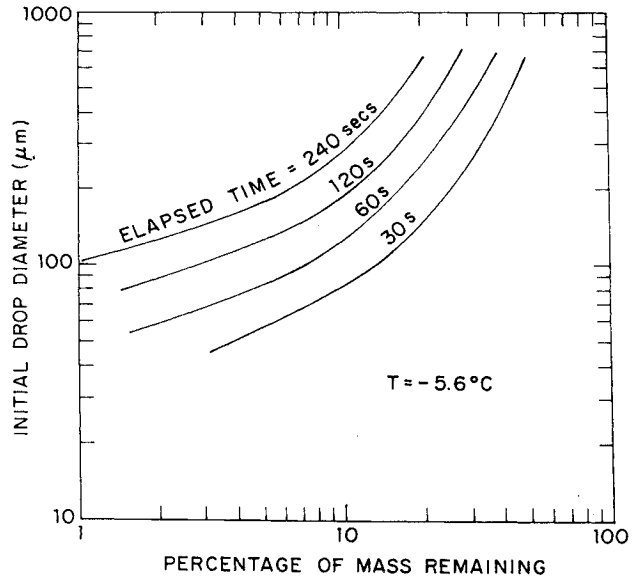

Fig. 4 Percentage of drop mass predicted in drops falling from 3730-m alt. Ambient temperature at 3730 m is −5.6°C.

profile, representing original or initial conditions, is constructed as a representative distribution of the original drop size and density distributions for all altitudes. The model distribution is shown in Table 2. The spectrometer data all show a maximum drop density occurring between 140 and 200 μm. Larger drops of 300 and 600 μm were observed with densities a factor of ten or more below the maximum density. The maximum measured density varied from a high of 7×10^{-3}g/m^3 to a low of 7×10^{-4}g/m^3.

The aircraft, in flying through the vent, frequently had the windshield covered with small drops similar to that encountered when driving through fog. These encounters were recorded as splash events and provided another indication of drop size. While the drops hitting the windshield could not be directly sized, the fall rate of these drops could be estimated from repeated encounters during a given sortie. Fig. 6 shows the time history of windshield splash encountered during Sortie 4/4. The drops fall rapidly during the first 100 s to approximately 150 m below the vent under the influence of the aircraft wake vortex. Thereafter, the drops are in free fall. For three sorties the terminal velocities were 52, 37, and 35

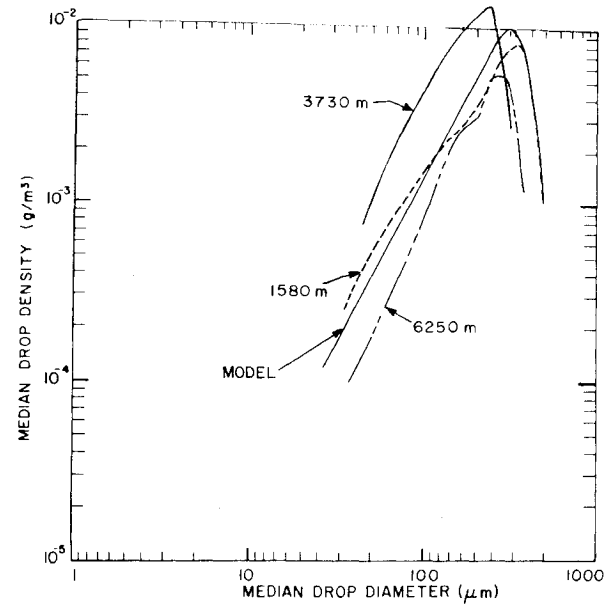

Fig. 5 Summary of original drop size distributions estimated from measurements of JP-4 vented at 1580-, 3730-, and 6250-m alt.

cm/s. These fall rates are representative of 120-160-μm drops. Thus, the windshield "splash" encounters are consistent with the probe spectrometer measurements.

The physical dimensions of the dump are important to defining the total mass balance. Hoshizaki[15] has developed scaling laws based on contrail photographs. The aircraft wake age is scaled to a characteristic time τ

$$\tau = \frac{\rho U b^3}{W} \tag{3}$$

where W is the aircraft weight, ρ the atmospheric density, U the aircraft speed, and b the aircraft wing span. Measurements of these parameters at the time of the fuel venting were used to determine the characteristic times as ranging between 9-10 s at 1580-m alt, 10-11 s at 3730 m, and 12-13 s at 6250-m alt. A 100-cm tracker camera was located directly under the fuel vent to observe the width of the vent. The vent width in units of wing span could be directly read from the film which also recorded the KC-135. Observations could be conducted out to $t/\tau \simeq 7$ after which time the film frame was filled. The results shown in Fig. 7 follow the Hoshizaki model for the jet and vortex regimes. It is apparent that the vortex region starts at $t/\tau = 5$ for the case of the KC-135. A long time is required because the fuel is vented at the dividing line between the two wing tip vortices. The fuel is not initially trapped in the vortex as is engine exhaust. The fuel is dispersed outward after the vortices have begun to interact, which occurs during the vortex dominated regime. Similar measurements were made for the vent height using photographs taken from side viewing cameras. Using the

Table 2 Model distribution

Drop diameter, μm	Drop density, g/m^3	Total density in size range
$40 \le d \le 300$	$\rho(d) = 3.67\times10^{-7}d^{1.8}$	0.008
$300 \le d \le 350$	$\rho(d) = 1\times10^{-2}$	0.0015
$350 \le d \le 1000$	$\rho(d) = 0.01e^{-(d-350)/100}$	0.0018
		0.01g/m^3

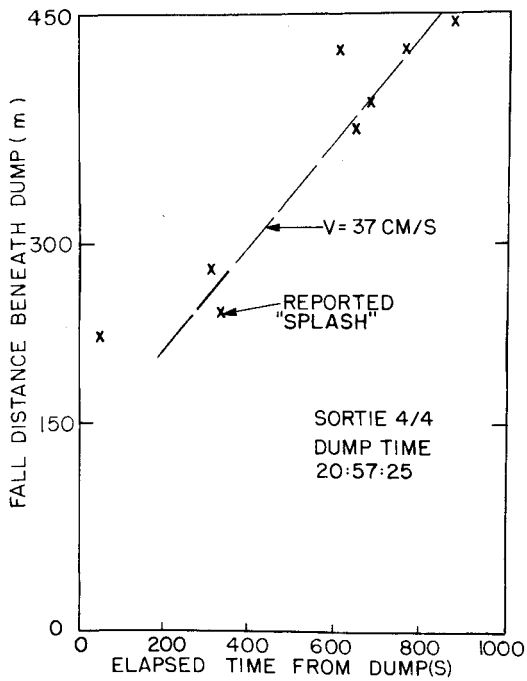

Fig. 6 Fall distance of drops observed by impact on sampling aircraft windshield. Fuel dump was at 6250 m.

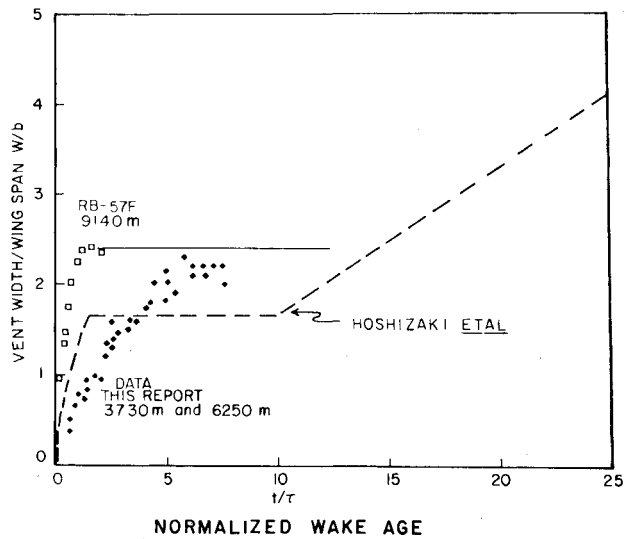

Fig. 7 Photographic observations of fuel-vent width as a function of age.

Hoshizaki scaling laws with adjustment for the actual vent trail, the vent cross section is estimated as follows:

t/τ	Height, m	Width, m	Nominal time, s
5	110	84	60
7.5	130	84	90
15	200	98	180
25	240	160	300

There does exist considerable JP-4 mass in the form of hydrocarbon vapor. The gaseous or vaporized fraction of JP-4 present in the vent was measured with an organic vapor analyzer. The largest value of vaporized JP-4 measured was 3.8 ppm. This represents a vapor density of 3.8×10^{-3} g/m^3 and a measured vapor density per vent length of 38 g/m. The KC-135 was venting fuel at a rate of 330 g/m. Thus, the measured vapor content represents approximately 11% of the fuel vented. At the time of observation, the observed drops

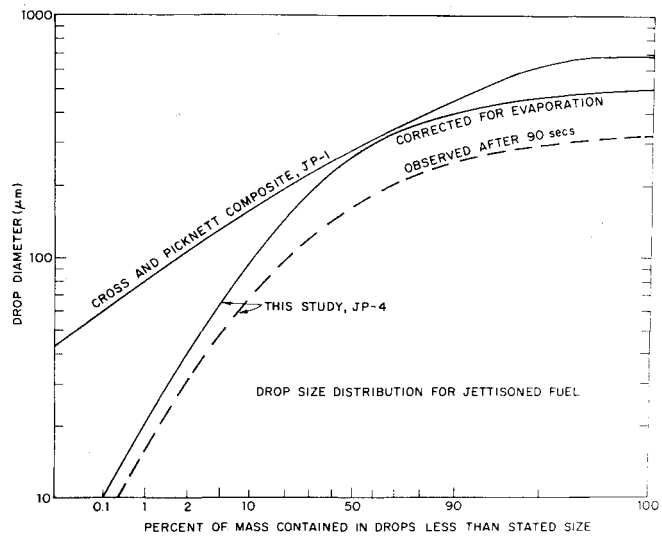

Fig. 8 Drop size spectrum of JP-4 vented from KC-135 aircraft.

contain 20% or less of the fuel mass. A vapor content larger than 11% should have been observed. The instrument calibration was reviewed and determined to be correct. Calibration gases consisting of 100 and 1000 ppm methane were used to calibrate the instrument both prior to flight and during flight. The instrument time response was more than adequate. Both direct and reverse flow air inlets were used with little change in measured hydrocarbon vapor. While no discrepancy could be determined in the analysis of the hydrocarbon measurements, it is nevertheless believed that incorrect results were obtained.

A determination of the mass balance is made using estimated original drop size and density distribution. The model distribution drawn in Fig. 5 represents a total density of 0.01 g/m^3 or 100 g/m. Within the uncertainty range of three, observed in the density measurements, the total mass in drops at the start of the vent equals the fuel vent rate of 330 g/m. On the basis of the evaporation model and the observed drop spectrum, it is believed that the fuel vented is all accounted. The model drop distribution can be scaled up by a factor of three to achieve a mass balance with the fuel vented and still remain within the scatter of observations.

The drop size distribution for the jettisoned fuel, using the model distribution, is determined in terms of percent mass contained in drops less than the stated drop diameter. The results of integrating the original drop density spectrum are shown in Fig. 8. This represents the best estimate for the drop size mass distribution of JP-4 vented from a KC-135 aircraft. For the KC-135 aircraft venting procedures, the median drop diameter, i.e., the diameter representing 50% of the mass, is 270 μm.

The present measurements were conducted at approximately one speed range and with a single nozzle size. It is important to determine what scaling exists with nozzle size and air speed. Merrington and Richardson found a scaling law,

$$V\bar{d}/\nu_d{}^{0.2} = \text{const} \tag{4}$$

It is important to note that the velocity V in this scaling law is the relative velocity between the aircraft and the fuel jet

$$V = U_{\text{aircraft}} - v_{\text{fuel}} \tag{5}$$

In the case of the KC-135 venting, the fuel venting is 10% of the aircraft speed. This was not the case for Merrington and

Table 3 Summary of mean drop diameter measurements

Vent diam, cm	Liquid	$\bar{d}$,μm	V, m/s	$V\bar{d}/\nu^{0.2}$	Reference
0.1-1.7	Water	1000	20-40	443	Merrington and Richardson
6	AVTUR	275	116	505	Cross and Picknett
6	AVTUR(JP-1)	350	116	645	Corrected for evaporation
10.1	JP-4	270	144	623	This study

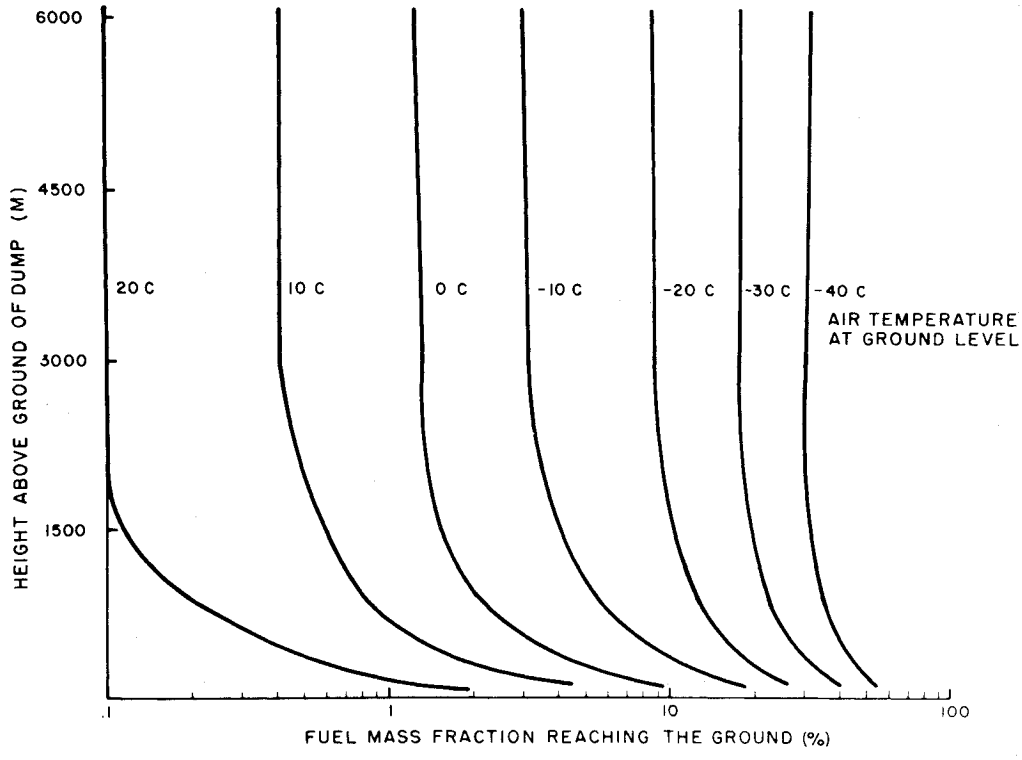

Fig. 9 Percentage of JP-4 liquid fuel drops predicted to reach the ground as a function of dump altitude, ground temperature, and adiabatic lapse rate.

Richardson. The existing flight data in terms of median drop diameter can be summarized in Table 3.

The scaling between this study and Cross and Picknett, corrected for evaporation, is excellent. However, the diameter range, 6-10.1 cm, is not large. It is unfortunate that the Merrington and Richardson data do not agree with the latter results. The difference could be due to invalid evaporation corrections or to an unknown dependence on the relative velocity. Further experiments are necessary to elucidate valid scaling laws with relative velocity and nozzle diameter.

The question as to the fraction of unburned fuel that will reach the ground can be determined using the initial drop diameters and the drop evaporation model. Fig. 9 shows the percent of fuel mass reaching the ground as a function of venting altitude for a variety of surface temperatures. Except for very low altitude releases, the fraction of fuel which reaches the ground is primarily determined by the temperature at the surface. For fuel vented higher than 1500 m and at temperatures above 0°C, less than 2% of the fuel will reach the ground. Although increasing altitude above 1500 m does not increase evaporation, it does increase the time for dispersion, reducing the fuel concentration at the ground. We can estimate the worst case fuel vapor concentration at the ground by assuming the fuel is jettisoned parallel to the wind under unstable atmospheric conditions. The highest ground concentration will be produced when the vertical mixing is maximum since then the fuel cloud will have less time to be horizontally dispersed. A profile of eddy diffusivity (K) in the mixing layer[16] shows that K is generally less than 100 m^2/s. We can estimate the vertical dispersion σ_z from the relation $\sigma_z^2 = 2K\,t$. For a Gaussian diffusion profile, the maximum ground concentration is reached when the standard deviation σ_z equals $z_i/\sqrt{2}$. Using a value[16] of $\sigma_z = 14.4\,t^{1/2}$, where t is in seconds, to represent strong vertical mixing, the maximum ground concentration for fuel vented at 1500 m is reached at 90 min. Horizontal transport during this interval can be approximated[17] by $\sigma_y = 0.5\,t$. Therefore, at a venting altitude of 1500 m, the majority of the fuel vapor will be spread crosswind for more than 5 km. In contrast, fuel vented at 6000 m would be spread over more than 90 km crosswind before it can reach the ground.

Ground concentrations of fuel vapor will depend on the fuel jettisoning rate and the aircraft speed. A KC-135 aircraft flying at 150 m/s and jettisoning fuel at 50 kg/s from an altitude of 1500 m will produce a fuel vapor concentration of less than 50 $\mu g/m^3$ at the ground. This concentration is well below the ambient air quality standard of 160 g/m^3. Most other aircraft jettison fuel at a much lower rate and would produce a correspondingly lower vapor concentration. Such low hydrocarbon vapor concentrations are unlikely to produce any negative environmental effects.

It is unlikely that fuel venting from other aircraft would produce the same droplet distribution as the KC-135. However, the use of droplet distributions with mass median diameters[6] ranging from 215-275 μm did not change the fraction of mass reaching the ground by more than 50% from

the value shown in Fig. 9. The effect of venting commercial jet fuel (Jet A or JP-8) instead of JP-4 is not certain. Lowell's[7] rule of thumb, mentioned previously, applies only to initial droplet evaporation rates. Preliminary calculations indicate that the fractional mass of commercial jet fuel reaching the ground at, for example, 0°C will be somewhat between the curves for JP-4 at −20°C and −40°C.

V. Conclusions

Observations of JP-4 vented from the KC-135 aircraft were conducted at three altitudes. The fuel drop size and density were measured, and a drop size density spectrum was determined. The drop size distribution was sampled in-flight after significant evaporation is known to have occurred. The observed drop size distribution was corrected for evaporation using a multi-component model of JP-4, and the original drop size distribution was estimated. The results show that the KC-135 venting procedure produces 270-μm median diameter drops. Applying a model of droplet free fall and evaporation to the estimated initial droplet size distribution, predicts that more than 98% of fuel jettisoned above 1500 m at ground level temperatures over 0°C will evaporate before reaching the ground. Droplets and vapor will be widely dispersed by winds, quickly resulting in a fuel density too low to create any perceptible changes in atmospheric composition.

These conclusions are based on JP-4 jet fuel vented from a KC-135 aircraft. However, the general results are considered to be applicable, at least for rough estimates, to other aircraft and jet fuels. Scaling these results accurately to other fuel vent nozzles and aircraft speeds cannot be done without additional experiments. Indications are for the formation of larger drops if the aircraft speed is slower or if the fuel is vented as a higher flow rate. In general, the aircraft should fly fast and dump fuel at a slow rate to assure that liquid drops do not reach the ground. Venting fuel 1500 m above the ground is recommended to permit the fullest time for evaporation.

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