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Post-Crash Fuel Dispersal

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ABSTRACT

This paper is a brief overview of work over the last several decades in understanding what occurs to jet fuel stored in aircraft fuel tanks on impact with the ground. Fuel dispersal is discussed in terms of the overall crash dynamics process and impact regimes are identified. In a generic sense, the types of flow regimes which can occur are identified and general descriptions of the processes are given. Examples of engineering level tools, both computational and experimental, which have applicability to analyzing the complex environments are presented. Finally, risk based decision is discussed as a quick means of identifying requirements for development of preventative or mitigation strategies, such as further work on the development of an anti-misting agent.

INTRODUCTION

Large energies are involved in the crashing of aircraft into the ground. Gross take-off weights for large transport or bomber aircraft can run into the 10^5 kg range. With flight velocities in the 10's to 100's of meters per second, the kinetic energy of impact ($1/2mV^2$) can run into the 10^9 J range. In addition, the fuel contained in the wing tanks of these aircraft can run into the 10^4 to 10^5 kg range. The typical energy contained in jet fuel that can be liberated on combustion is 4.3×10^7 J/kg. Therefore, the amount of energy available is on the order of 10^{12} J. These energies are substantial by almost any measure with the energy available from combustion potentially several orders of magnitude higher than the kinetic energy on impact.

Due to the energies involved, a crash can result in the destruction of both materials and personnel. Statistics delineate the magnitude of the effect (Boeing 1996). From 1959 through 1995, 65% of accidents which resulted in damage to the aircraft beyond economic repair also resulted in fatalities. Over the same period, less than 4% of accidents resulting in substantial but repairable damage resulted in fatalities. From 1991 to 1995, 71% of the fatalities were from loss of control in flight or controlled flight into terrain. Other statistics indicate that for 'crash-survivable' accidents, 40 percent of deaths are due to fire (20% of total fatalities) (FAA, 1991). Due to the high energy content of the fuel and statistics which attest to the effect of fire, understanding the fuel and its state in the post-crash environment are important, even in the presence of ground based fuel in the impact area.

The role of fuel dispersal in the post-crash environment can best be described if the crash environment is viewed as a process, albeit an undesirable one. At the highest level, as shown in Figure 1, the crash process can be thought of as a set of initial conditions (crash scenarios) leading to a set of undesirable events (combustion modes), leading to a set of unfortunate consequences (death and environmental impact). Two generic strategies are available to interrupt these undesirable processes. Prevention seeks to stop the undesirable event from occurring while mitigation seeks to reduce the consequences of the accident.

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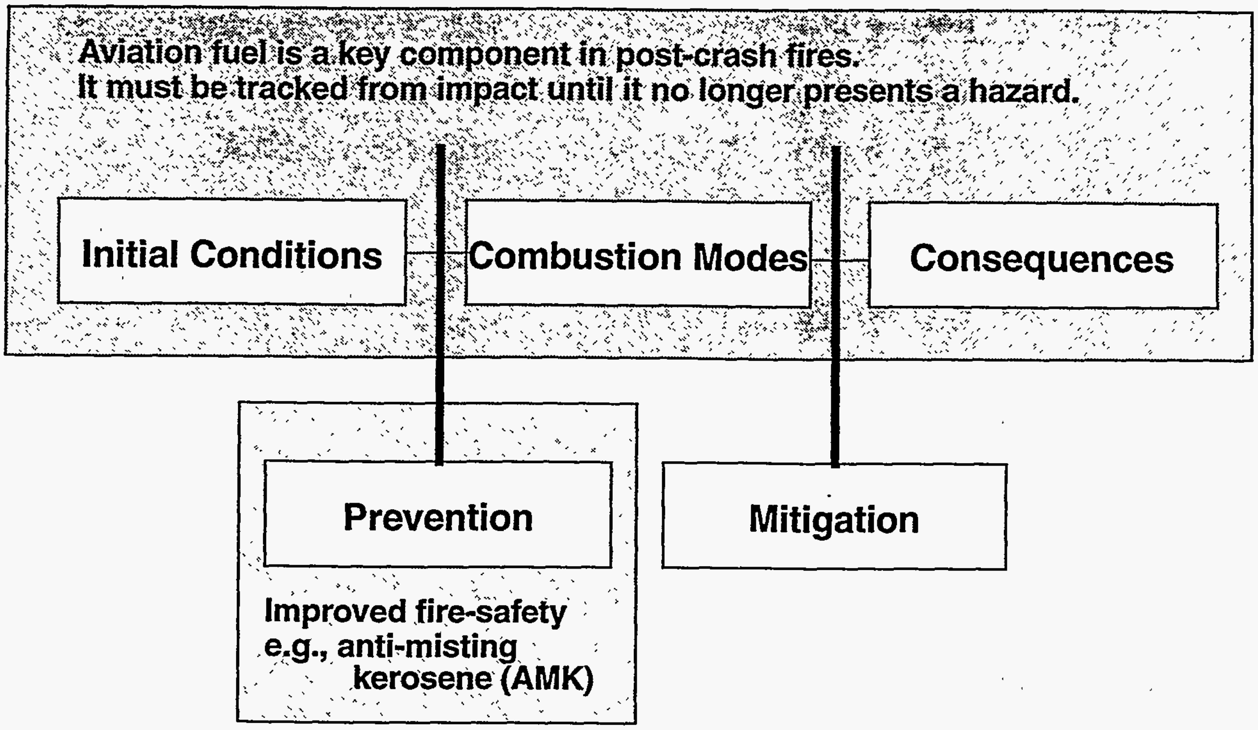

Figure 1. Dual Role of Fuel Dispersal in Aircraft Impact From a Process Perspective.

Within the context of the process shown in Figure 1, fuel dispersal plays two major roles. The first role is within the process description itself. Jet fuel is a major source of combustible material in a crash environment, and therefore, must be tracked from the moment of impact until such a time it is either consumed by fire or it has traveled sufficiently far from the aircraft that it no longer represents a significant hazard.

Since jet fuel is a major contributor to post-crash fires and fires are a major contributor to deaths, it is only natural to seek a preventative strategy within the fuel makeup itself. Obviously, the ideal solution would be to have a fuel which will burn with great vigor in an engine, and absolutely will not combust anywhere else. Until someone achieves this idealistic goal, less effective fire prevention strategies will need to be employed.

Before one can begin effective development of preventative or mitigative strategies for an undesirable process, one must first define the process to the extent that concrete design objectives can be set for prevention and mitigation strategies. While this statement is obvious, its importance cannot be overemphasized. Cost minimization places higher emphasis on fixing an undesirable process rather than on defining the process. However, attempts to fix a process without quantitatively understanding how that fix will affect the process can lead to higher overall costs, and often less than optimal results. Unfortunately, the more complex and nonlinear the process, the more difficult it is to quantify the process, and hence, the more likely it is to have an unsuccessful outcome from development work on a preventative or mitigative strategies. Aircraft crash sequences are very complex, nonlinear processes.

In general terms, fire prevention strategies attempt to separate one key element of fire from the other two. The three key elements are fuel, air, and an ignition source. Since air is ubiquitous, the separation of it from the other two is questionable except in specific situations such as in-flight inerting of fuel tanks. This leaves the separation of ignition sources from the other two, or fuel from the other two. An example of an ignition source strategy is to foam a runway prior to landing if it appears a crash may be likely. However, there is not much that can be done to totally eliminate ignition sources since hot running engines are a requirement for aircraft flight and hot brakes are likely to occur in any sliding accident. The separation of fuel from the other two fire elements has taken two general forms, fuel tank impact structural integrity improvements, (crashworthiness) and a long running attempt at developing an anti-misting agent for jet fuel (AMK).

Fuel dispersal in the context of an aircraft crash is discussed in the next section followed by qualitative descriptions of the processes involved in fuel dispersal. Tools are then discussed for addressing fuel dispersal including engineering computational and experimental tools, and a description of risk based decision as it could be applied to this problem. As will be seen, the flow regimes for fuel are manifold. Therefore, the scope of this paper is limited to qualitative descriptions and the tools shown are to be taken as representative in nature, not comprehensive. Further, due to the broad nature of the flow regimes, it is not possible to cover the extensive fundamental research in fluid mechanics which underpins our understanding of the flow regimes in any realistic way, so no attempt is made in this paper.

Fuel Dispersal In The Context of A Crash

Figure 2 shows an aircraft impact as a series of processes verses time. These processes fit within the overall description in Figure 1. From the time of impact until the aircraft motion is terminated, tremendous energy is being dissipated. During a routine landing this energy is being dumped into the brakes, tires, and through thrust-reversers into the air. In a crash, this energy can further be dumped in abrasion of fuselage or other parts that are skidding along the ground, or in large-scale deformation upon impact with a solid object, all of which can produce either sparks or hot surfaces for ignition. At sufficiently high impact energies, a fuel tank may fracture and begin to leak. The loss of control of geometry results in the process of fuel dispersal. The actual processes involved in fuel dispersal will be discussed in the next section.

These energy dissipation processes form the initial conditions for a fire as discussed with respect to Figure 1. The role of preventative strategies is to interrupt these processes such that, over some specified impact regime such as 'crash-survivable', the effect of the preventative strategy is to block the formation of fire by preventing fuel, air, and an ignition source from simultaneously occupying the same spot in space.

If fuel vapor, fuel droplets, or sheets of fuel on the ground come into contact with an ignition source, then ignition can occur and the fire can spread. In a general sense, fire spread can be thought of as a continuous ignition process with the existing fire being the ignition source. In this way, a large fireball that would result from the ignition of a fine mist provides a very strong ignition source for further spreading of the fire to discontinuous fuel segments via radiative heat transfer. Potential ignition sources range in duration and scale from the large fireball lasting several seconds, through fragmenting engines parts and brakes which can be hot for minutes, to ubiquitous small scale sparks which exist for the briefest of milliseconds (Tilston, 1989). Once the fire has spread, combustion of the fuel occurs until it is depleted or firefighting measures become effective. Combustion processes can take several modes depending on the state of the dispersed

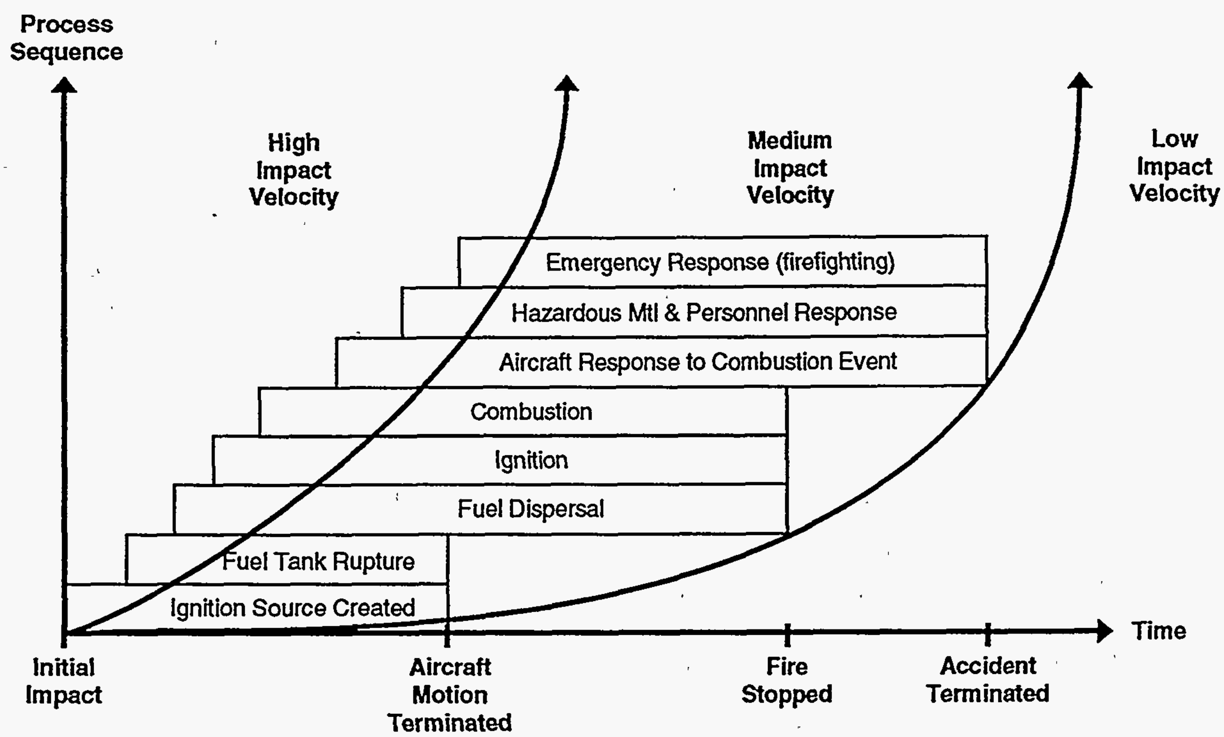

Figure 2. Processes Involved In Aircraft Crashes as a Function of Time. Note: The impact velocity regimes are defined in Figure 3.

fuel. The modes range from a fireball, to a fire above a continuous liquid pool, whether stagnant (called a 'pool fire') or replenished (called a 'spill fire'), to a fire above soil saturated with fuel (called a 'dirt fire' herein).

The ignition and combustion processes form the combustion modes for a fire as discussed with respect to Figure 1. The role of mitigative strategies is to impact these processes such that, over some specified impact regime such as 'crash-survivable', the effect of the mitigative strategy is to block the spread of fire into the cabin area or to reduce the thermal/toxicity consequence of the fire on humans and/or hazardous cargo (chemical, biological, or nuclear). Examples of this type of strategy include the development of fire- and smoke- resistant interior materials. (National Research Council, 1995).

The consequences of a fire are both thermal and chemical (toxicity). The aircraft provides some protection to occupants inside depending on the damage levels sustained and environmental conditions such as wind. In general, the consequences of a crash can be impact trauma, thermal trauma, or both. The term 'crash-survivable' typically refers to the regime in which humans can survive the impact trauma. While useful in this regard, 'crash-survivable' conditions for hazardous material transportation containers or a nuclear weapon are typically much broader than for a human and therefore the term can become rather confusing unless the object to which it applies is referenced.

Another manner of categorization is to divide the regimes by the basic process character as a function of impact velocity. This categorization is shown in Figure 3. While this categorization

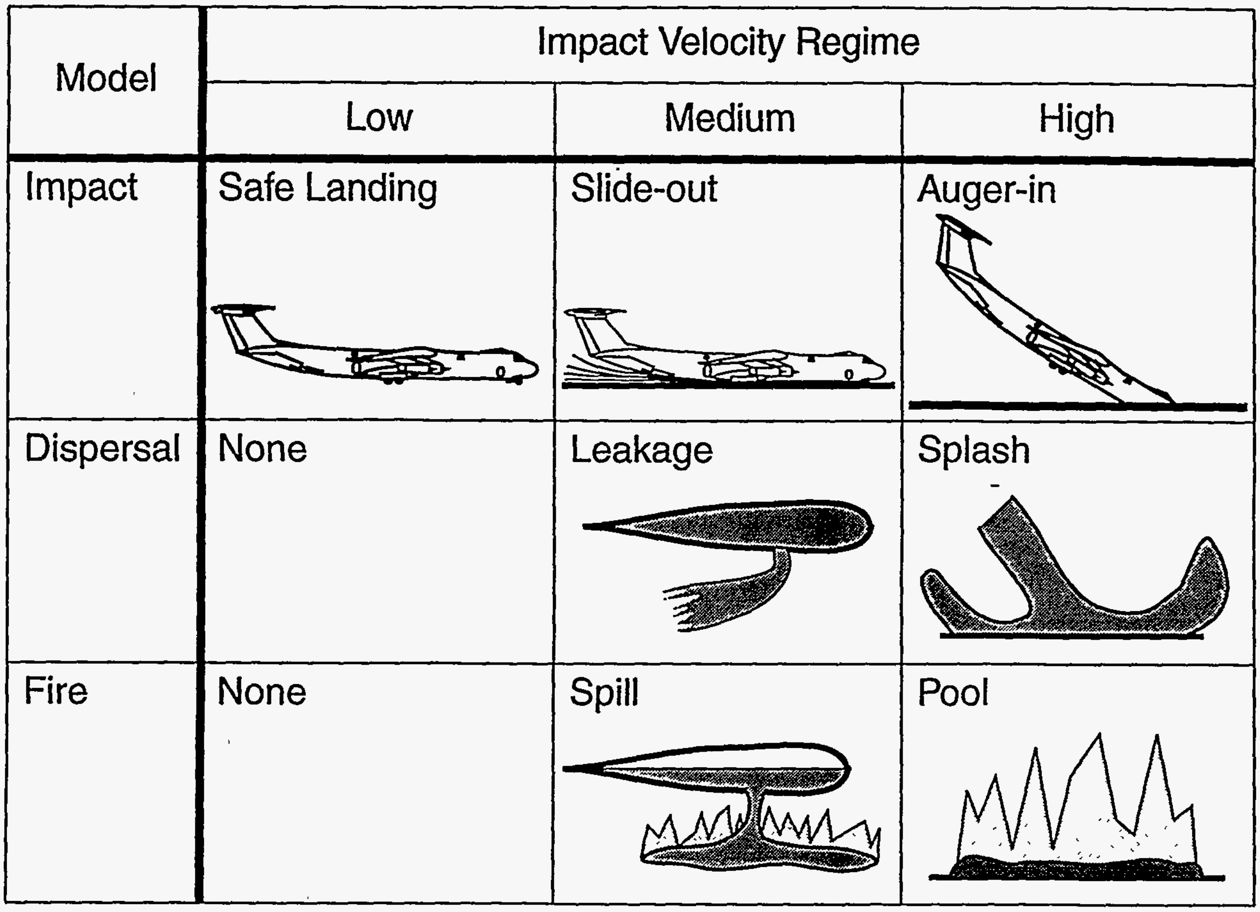

Figure 3. Classification of Crash Scenario by Impact Velocity

is less insightful on the ratio of impact to thermal survivability, it is more insightful to physical processes which occur in an accident. Accidents can be broadly characterized as 'sliding out' or 'augering in' (Kuchta and Clodfelter, 1985, Tieszen, 1995) depending on their normal impact velocity. By 'normal' impact velocity, it is meant the velocity perpendicular to the surface. At low normal impact velocities, a plane lands safely. Above a certain normal impact velocity level, as characterized by landing gear failure, for example, a transition occurs to the medium impact velocity regime. At medium normal impact velocities, the crash can be characterized as a slideout in which the plane slides along the ground. The fuel tanks can be characterized as being damaged in this regime but not fragmented. Fuel dispersal occurs by leakage from the damaged tanks. Ignition may result in a small to moderate fireball. After the aircraft comes to rest, pouring fuel will result in a long duration spill fire. At higher levels of impact velocity, the plane and fuel tanks basically fragment as the plane augers in. The fuel disperses in a large splash. Ignition results in a large fireball. Remaining fuel on the ground burns as a pool or dirt fire.

The separation between the medium and high impact regimes is somewhat arbitrary. However, for reference, Wittlin, 1987, concludes that a distributed-load wing impact (such as striking a low hill or mound with the wing) between 60 and 72 m/sec will devastate the wing fuel tanks. For concentrated loads (such as a telephone pole) the velocity at which the wing tanks will be destroyed is even lower, 33 to 41 m/sec, depending on the type of obstacle. For reference, jet flight speeds are well above this range.

Therefore, any impact into the side of a steep mountain or building can be considered of the high impact velocity type. Airports are increasingly being engulfed by the growth of cities, in part because of the commercial opportunities provided by the airports. That engulfment and the fact that close to 50% of all fatalities occur during approach and initial climb (Boeing, 1995), suggests to the author that accidents will increasingly be of the high impact type because of the vertical nature of the impacted surface (i.e., the sides of buildings). It further suggests that the ratio of ground to aircraft fatalities may increase with time.

The impact velocity regimes in Figure 3 can be qualitatively mapped onto the timing of crash processes as shown in Figure 2. The faster the impact velocity, the earlier in the crash transient that each process begins. If an aircraft lands safely in the low impact velocity regime, then the impact energy is dissipated in brakes and thrust-reversers and no accident results.

Fuel Dispersal Processes - Medium Velocity Impacts

Since the 'crash-survivable' regime for humans is wholly contained within the medium velocity impact regime, the principal source of study for this regime has been the long running FAA program on the development of anti-misting kerosene which ended in 1986 (Yaffee, 1986). The program conducted a dozen full scale impact tests between 1965 and 1984. Structural issues regarding fuel tank failure and crash resistant design can be found in Nissley and Heid, 1964, Buckson, et al, 1965, Schauerman, 1971, Hackler, 1972, and Wittlin, 1987. Characterization studies of anti-misting fuels can be found in Ahlers, 1970, Miller and Wilford, 1971, Russell, 1971, Rockow and Shaw, 1972, Faul, 1978, Salmon, 1981, Mahood and Talley, 1982, and Parikh, et al, 1983. Other crashworthiness programs have also been conducted within the DoD community, see for example, Shaw, 1971, and Johnson, et al, 1989.

The primary goal of these studies was the development of anti-misting kerosene. Direct measurements of fuel dispersal, without an anti-misting agent, are quite limited. A summary of the data as it relates directly to the physical processes involved in fuel dispersal can be found in Tieszen, 1995.

Heuristically, the processes involved in fuel dispersal in the medium impact velocity regime are shown in Figures 4 and 5. Figure 4 shows the dispersal stages prior to ignition of the fuel. Initially, upon impact with the ground, the fuel in the tank will be subject to inertial loads due to the rapid deceleration of the aircraft on impact (in addition to the gravitational force). As a result the fuel will slosh within the tanks to adjust to the time-varying inertial force. Since the fuel mass is usually many times the wing mass, the inertia of the fuel and its compressibility are important in determining the impact dynamics of the fuel tank, thus influencing the damage state that results from the impact. With a puncture or tear of the fuel tank, inertial and gravitational forces will create a flow out of the tank. The rate of fuel leakage from the tank will be proportional to the damage caused (hole area), and the forces present.

The next stage of dispersal occurs as the force balances change on the fuel emerging from the tank. The fuel stream is subject to a free, pressure boundary just outside the damaged tank. During slideout, there is relative motion between the aircraft and the surrounding air. As a result, the total pressure against the fuel stream changes rapidly as it traverses the boundary layer between the tank surface and the free stream. Due to the destabilizing processes of aerodynamic drag and turbulence within the fuel itself, a sequence of breakup processes begin which result in

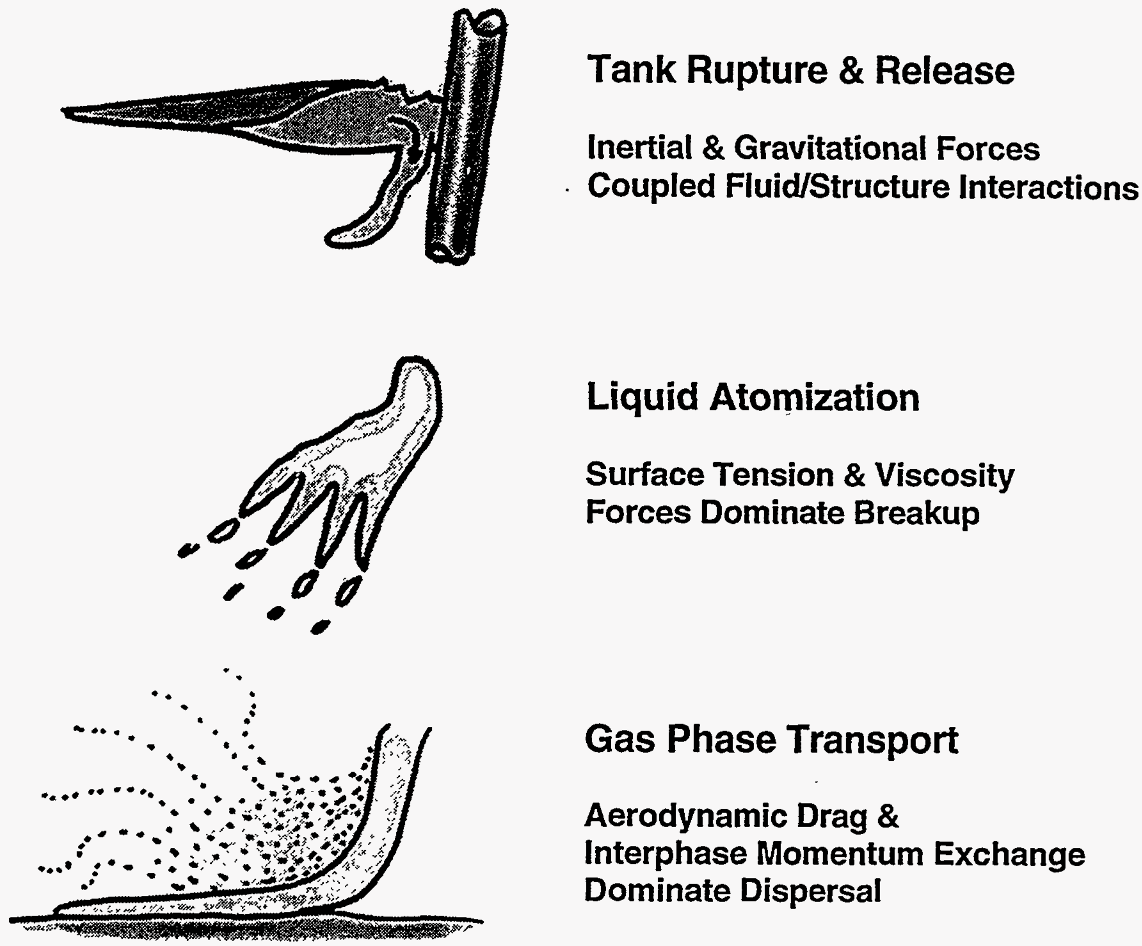

Figure 4. Stages of Pre-Ignition Fuel Dispersal in the Medium Impact Velocity Regime.

the atomization of some fraction of the fuel. Initially, drops are shed from the liquid column and under certain flow regimes the whole column may break-up into sheets, ligaments, and drops. Surface tension is the primary force resisting breakup. However, the breakup process occurs in regions of high spatial and temporal gradients, so rate dependent forces such as viscosity, which acts to retard breakup, can affect the outcome.

The process by which a continuous liquid jet becomes atomized is termed primary breakup. An in-depth description of the processes can be found in the book by Lefebvre, 1989. Recent studies which show the importance of the effect of the turbulence in the liquid phase can be found in Wu, et al, 1992, Wu and Faeth, 1993, Wu et al, 1995, and Wu and Faeth, 1995. Two distinct flow streams can leave this stage of dispersal, airborne droplets that are the result of primary breakup and the residual fuel stream which will continue its fall until it impacts the earth.

For the airborne droplets, the next stage of dispersal involves secondary breakup and interphase momentum exchange with the air. Secondary droplet breakup can occur if the drops are large and the velocity difference between them and the gas is high. The secondary breakup process is also classically viewed as a balance between inertial and surface tension forces. If the

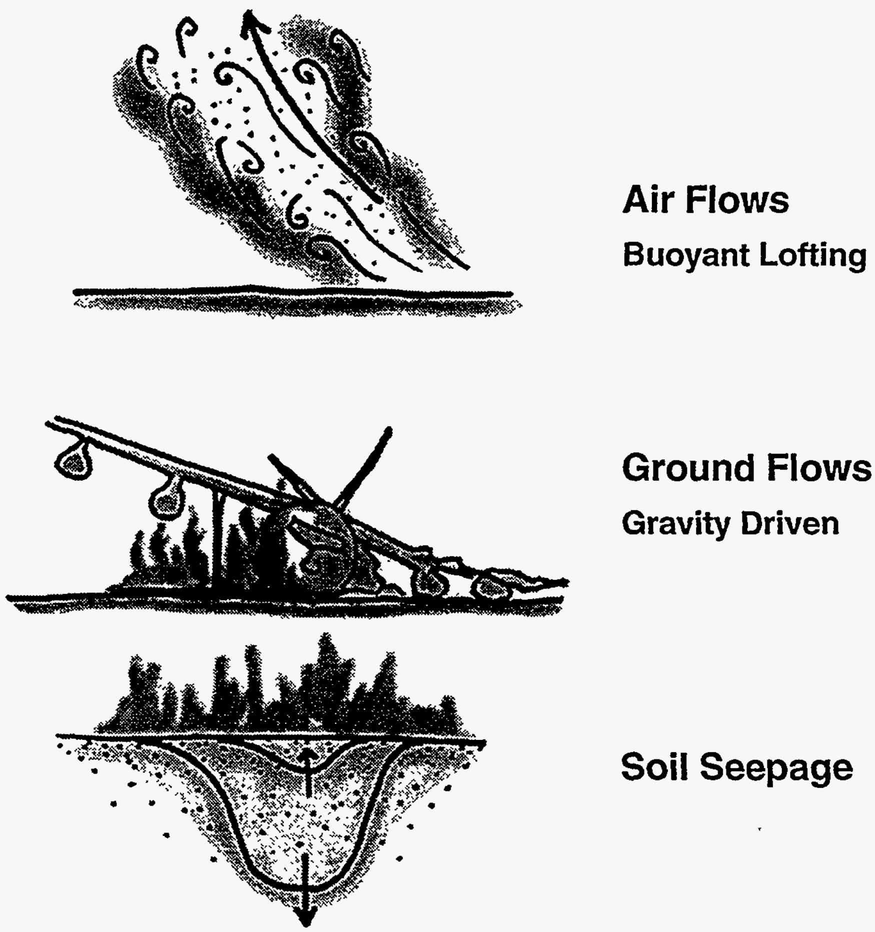

Figure 5. Stages of Post-Ignition Fuel Dispersal in the Medium Impact Velocity Regime.

drops are small, but many, then they can also coalesce back into larger droplets.

The final drop size distribution is important because it affects the rates of interphase momentum exchange which occurs continuously from the time the drops separate from the fuel stream. The momentum transfer distance can be quite short for small droplets, while larger droplets can travel for many meters. Given sufficient travel distance without impacting a solid surface, all droplets eventually reach an equilibrium settling velocity relative to the air due to gravitational acceleration. The transfer of momentum from the fuel stream to the air, while dissipative, does not imply a total loss of momentum. Rather the air acquires the momentum and subsequently transports the drops. The result of the interphase momentum exchange is a spray that can be transported via turbulent air motion over large volumes of space.

Depending on the amount of damage from to the fuel tank and the slideout velocity, the fuel flowing from the tank may not be completely atomized to the point that it will be significantly deflected by the air. The fuel stream, both as a continuous column and as discontinuous, partially atomized segments, will continue to fall under the influence of gravity until impact with the ground. Not all of the fuel impacting the surface as a liquid stream will remain on the surface after impact. Splashing of droplets off the surface back into the air will occur depending on the impact velocity and liquid turbulence levels (Errico, 1986, Lienhard, et al, 1992, Bhunia and Lienhard, 1994a and 1994b, Tieszen 1995). Depending on the fuel stream velocity upon hitting the ground, the flowing liquid can either be either faster than the gravity wave speed on the free surface, i.e., supercritical, or slower than the gravity wave speed, i.e., subcritical. If it is supercritical, a hydraulic jump will follow to reduce the velocity to a subcritical state. The subcritical fluid will continue to spread over the terrain. The fuel spread rate is then governed by several factors including gravity, the slope of the terrain, inertia of the existing fluid, and viscous drag on the solid surface (Didden and Maxworthy, 1982, Huppert, 1982, and Lister, 1992). Soil porosity will also affect the spread rate and size of the spill.

As noted earlier, fire can only occur in the presence of fuel, air, and an ignition source. An ignition criteria can be thought of as the instantaneous overlapping of the geometric regions for which ignition energies are present and for which an ignitable spray volume or liquid fuel stream is present. Viewed in this manner, determination of ignition requires the time-dependent, spatial tracking of energy sources and fuel streams for simultaneous co-location (accounting for action-at-a-distance mechanisms, such as radiative heating). For the spray, the key parameters are the concentration and size characteristics necessary to permit ignition and flame propagation. For the liquid stream, the key parameter is its spatial distribution. If, for all points in space and for all points in time during the accident transient, ignition sources and fuels can remain separate, then a fire will not result.

Figure 5 shows the stages of fuel dispersal after ignition of the fuel. Ignition of the mist can result in a fairly sizable fireball with the result being radiant heating of nearby fuel surfaces. Fireballs radiate energy for seconds to tens of seconds depending on the mass involved (Dorofeev, et al, 1991). Due to buoyancy induced by combustion, the fireball will loft and the combusting mist will be elevated with it. In this manner, fireballs are a quick means of consuming fuel. However, they also provide a large ignition source for fuel that might not otherwise be ignited. In addition to radiative heat transfer, a fireball can spread flames back along the fuel mist to the fuel source if the fuel mist has no discontinuous or non-flammable regions. The flame can then anchor onto the spill point on the aircraft.

Depending on the amount of damage from to the fuel tank and the amount of fuel in the tank at the time of the accident, fuel may continue to drain from the aircraft long after it comes to rest. If ignition occurs in the fuel on the ground, flame spread can result in the propagation of the flames back to the source if the fuel spill has no discontinuous or non-flammable regions. The flame can then anchor onto the spill point on the aircraft.

After the aircraft comes to rest, the flow of liquid from the tanks will primarily be gravity driven as described above. However, fire induced heating of the tanks may produce residual tank pressures that can contribute to the rate at which the fuel will leak from the tank. In addition the final size of the fire will be limited by the balance between the rate of evaporation by the fire and the spill rate (Cline and Koenig, 1983).

In addition to flowing over the ground, the fuel spill can also flow into the ground if the ground is porous and if the pores are not saturated with water. In addition to gravity, fuel is pulled into the ground by capillary pressure that is a function of pore size. By the same means, fuel that has flowed into the ground is not necessarily safe from being evaporated by and contributing to the fire. Evaporation from the fire will dry the surface of the soil. Fuel under this dry layer can be pulled up against the force of gravity by capillary forces to evaporate and feed the fire. Very long duration fires can be sustained in this manner depending on the soil properties.

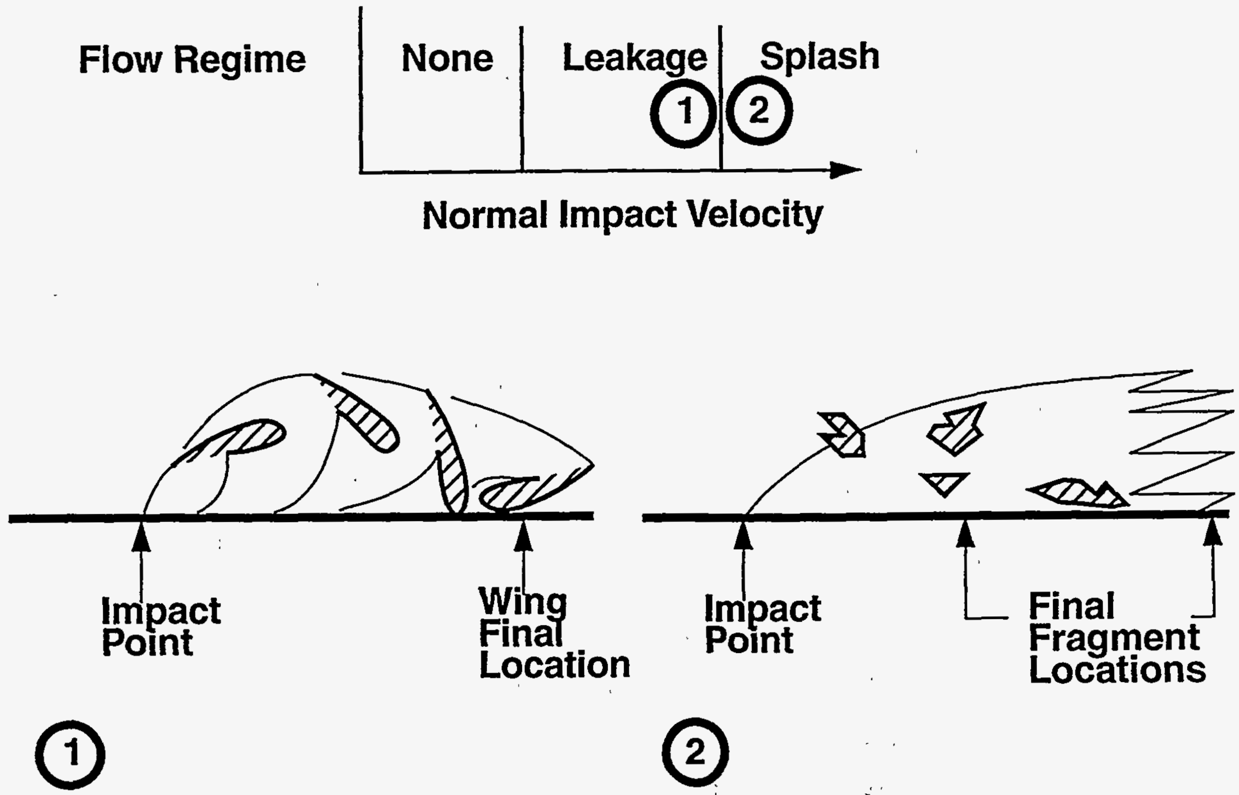

Figure 6. Transition from Medium to High Impact Velocity Regimes. A tumbling wing splashing fuel forward of an impact point becomes indistinguishable from a fragmentation impact.

Fuel Dispersal Processes - High Velocity Impacts

The impact regime has received less attention than the medium velocity regime. The lack of interest in this regime is not due to the lack of accidents occurring in this regime but human survival in this impact regime is problematic. The primary source of data for this regime has been Department of Defense studies, the most recent of which is the Defense Special Weapons Agency (DWSA) Fuel-Fire Technology Base program which has sponsored work in understanding fuel-dispersal (Tieszen, 1995, and Tieszen and Attaway, 1996) and fires (Gritzo, et al, 1995a, Gritzo, et al, 1995b, Nicolette, et al, 1995, and Tieszen, et al, 1996b) in post-crash environments. The primary goal of these studies is to characterize the post-crash environment to the extent that it affects nuclear weapon safety. Rather than an engineering development type of activity such as that undertaken by the FAA to develop a preventative measure, the approach of the DWSA program was to develop an understanding of the crash process to the extent necessary to build risk-assessment compatible models. Risk-assessments place significant solution time constraints on models since tens of thousands of scenarios are often run to develop statistical significance. As a result, the models focus only on the dominant physical mechanisms.

As noted with respect to Figure 3, the primary difference between the medium impact velocity regime and the high impact velocity regime is that the aircraft tend to slide out in the medium velocity regime and auger in the high velocity regime. The dividing line between the regimes is continuous, and therefore, somewhat arbitrarily set. Figure 6 shows examples near the

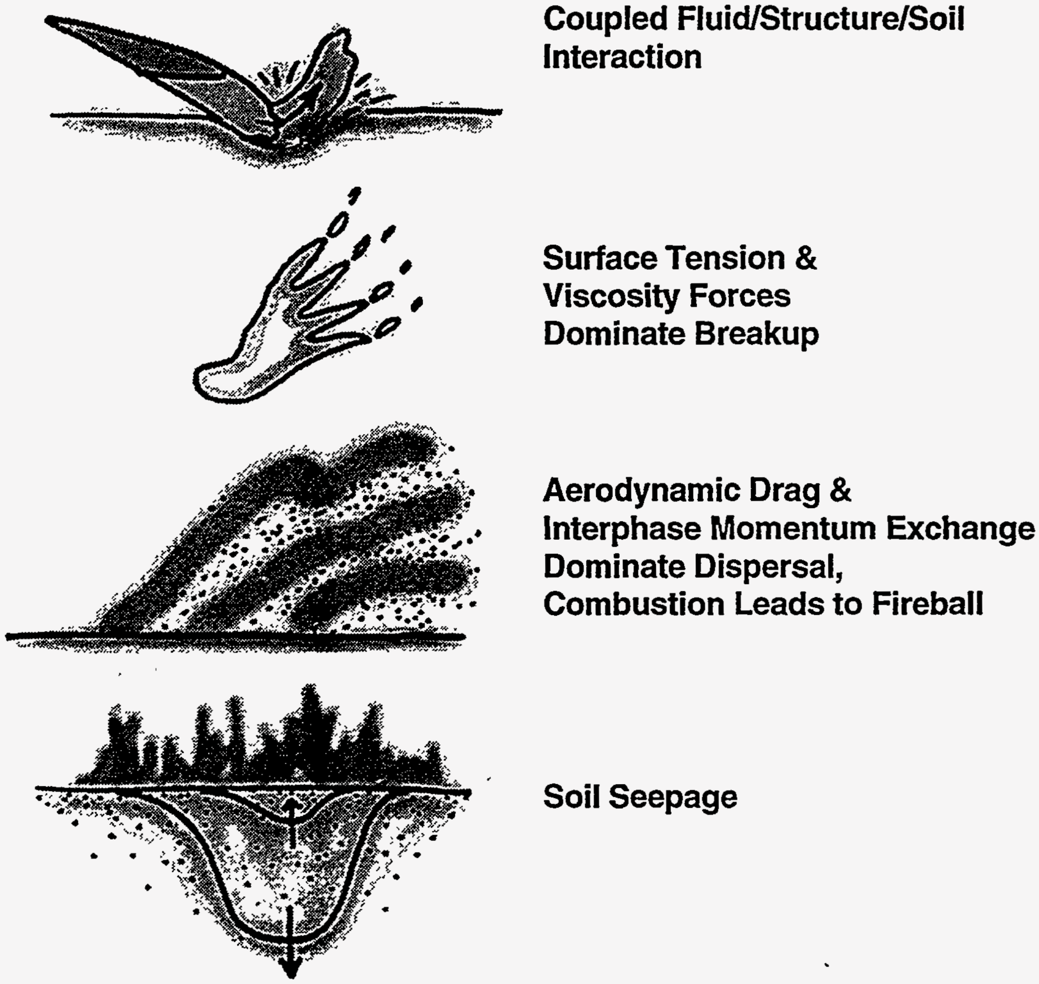

Figure 7. Stages of Fuel Dispersal in the High Impact Velocity Regime

boundary between the regimes. On the medium impact side of the regime, damage to the fuel tanks increases with increasing impact velocity. For example, a heavily damaged wing may separate from the fuselage and tumble down range, leaking fuel in the process. This type of accident begins to be indistinguishable from the high-speed impact in which the wing fragments on impact and the fuel and fragments are thrown forward from the impact.

Figure 7 shows the stages of fuel dispersal for the high impact velocity regime. In many respects, the flow regimes are not qualitatively different than in the medium impact velocity regime, although quantitative differences are likely. Note that in many instances, it is the angle of impact, not just the velocity that determines whether or not the impact can be of the high normal impact velocity type. An impact of any aircraft against the side of a steel building at any flight speed will result in fragmentation of the aircraft and "augering in" to the building.

Upon initial impact with the ground the fuel in the tank will be subject to inertial loads due to the rapid deceleration of the aircraft on impact. The compressibility not only of the fuel mass but also the compressibility of the surface which is impacted are important. If the surface is sufficiently hard, such as a concrete runway, then it may not crater. If the surface is sufficiently soft, such as a plowed field, then it certainly will. Studies have shown (Tieszen, 1995, and Tieszen and Attaway, 1996) that there is a distinct difference in the dispersal characteristics between cratering and non-cratering surfaces. This difference illustrates the effect of the inertial coupling and compressibility on the problem.

The next stage of dispersal occurs as the fuel emerges from the ground surface or crater. As with the medium impact velocity regime, the fuel stream is subject to a free, pressure boundary. Due to the destabilizing processes of aerodynamic drag and turbulence within the fuel itself, a sequence of breakup processes begins which results in the complete atomization of the fuel leaving the surface. Surface tension is the primary force resisting breakup. However, the breakup process occurs in regions of high spatial and temporal gradients, so rate dependent forces such as viscosity, which acts to retard breakup, can affect the outcome. The fuel that leaves the surface is likely to be completely atomized due to the large scale and high velocity associated with the impact (Tieszen and Attaway, 1996). However, not all the fuel in the tank leaves the surface in an accident that involves cratering. Upwards of 50% of the fuel can remain in the crater depending on the angle of impact (Tieszen and Attaway, 1996).

Due to the energies involved in impact and the intermixing of aircraft fragments with the fuel, ignition is very likely under these circumstances. Further, it would be very difficult to employ any mitigative strategy which sought to prevent ignition by maintaining physical separation of the fuels and ignition sources in this type of accident. Given ignition, the airborne fuel spray will result in a large fireball and be consumed. In the medium impact velocity regime the presence of the fireball acts to significantly increase the probability of ignition and in this sense is considered to be quite detrimental. In the high impact velocity regime, with ignition virtually guaranteed by intermixing, the fireball acts as a quick means of burning off the fuel. Often hazardous cargos are sufficiently hardened such that seconds to tens of seconds at fireball heat fluxes are not sufficient to damage the cargo. Rather, it is the long duration fires that present a more serious consequence.

The long duration fire can be one of two types. If the fuel in the crater is in the form of a continuous liquid pool, then the fire will be of the pool fire type. If the fuel pool is or becomes discontinuous due to seepage within the porous soil, then the fire can be sustained off the evaporation from the soil itself and is of the dirt fire type. The location, intensity and duration of this fire relative to hazardous cargo containers has been the principal concern for this type of accident.

Engineering Tools for Post-Crash Fuel Dispersal

Computational and experimental tools that have been applied to fuel dispersal problems of relevance are briefly addressed in this section. The purpose is not to be comprehensive but rather to give the reader a feeling for the types of tools and their uses. As has been discussed, the range of multiphase flow regimes that can result from fuel dispersal is extremely broad. For this reason, space does not permit a discussion of fundamental research tools and results. Tools and issues for four stages of dispersal are briefly covered, tank damage/destruction, fuel atomization, interphase momentum exchange, and ground flows.

The initial stage of fuel dispersal involves tracking the fluid out of the tank. Typically, compressibility is important. Computationally, the tool of choice for many years for this type of problem has been the transient, multidimensional hydrocodes. An example of the use of the CTH

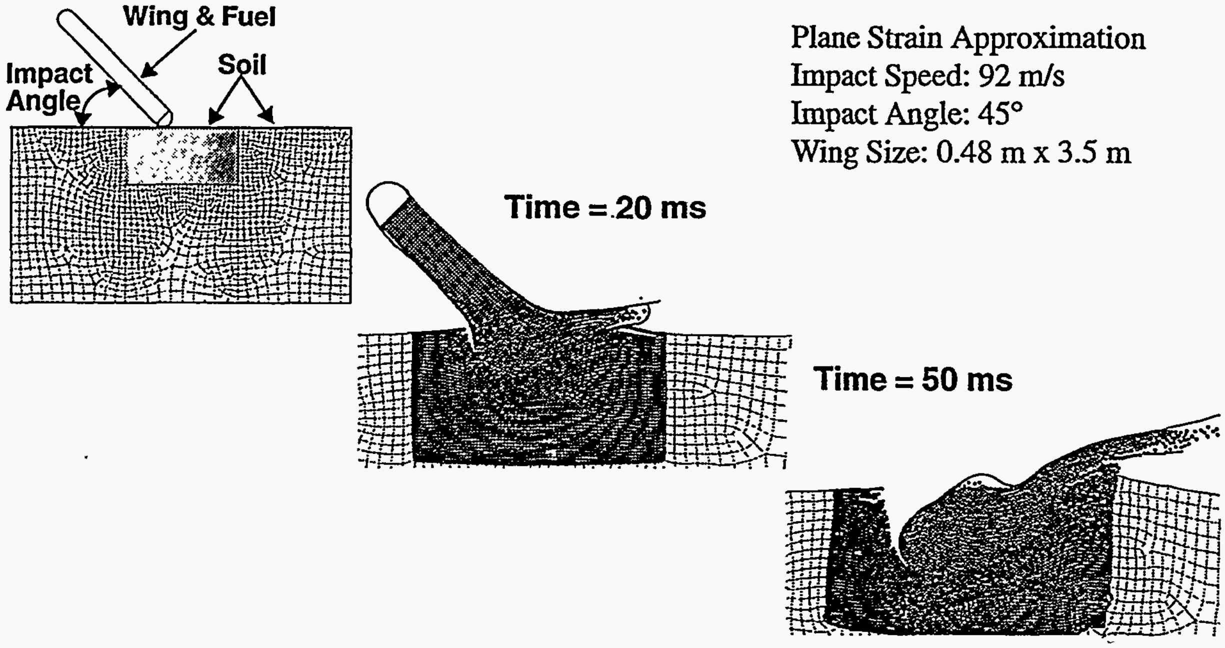

Figure 8. Example of Numerical Simulation Tool for the Impact Stage of Dispersal. Example of two-dimensional SPH calculation. From Tieszen, et al, 1996a.

computer code on a fuel dispersal problem is given in Gardner, 1990. Recently, a new approach has been developed which is easily coupled to standard finite-element based approaches which are now the norm for structural dynamics (Attaway, et al 1994). The new approach is called 'smooth particle hydrodynamics' (SPH). While not completely accepted for general fluid mechanics work yet, SPH has many advantages for short duration, high-strain rate, impacts (such as its gridless formulation which allows large mesh deformation without entanglement).

Figure 8 shows an example two-dimensional calculation (Tieszen, et al, 1996). Shell elements which represent the wing skin can be used in the same formulation as the gridless integration points. Both the fuel in the wing and the soil in the near impact region employ the smooth particle integration points. While the method allows for differing equation of state formulations, the time step must be very short to take into account compressibility effects. For this and other reasons, the technique is not particularly suitable for tracking the fluid beyond the impact and breakup of the tank into the atomization regime.

Figure 9 shows a photograph of a small gas gun that was used to establish the suitability of the SPH approach for liquid/soil impacts (Tieszen and Attaway, 1996). This type of facility is representative of many impact facilities within the federal laboratories used for impact type work. While very few facilities have been used directly for dispersal studies as has the one shown in Figure 9, many could be modified to cover the range needed for dispersal work. Impact facilities exist within the Department of Defense (all services), Department of Energy, and Department of Transportation. Impact facilities range in scale from several feet long (Figure 9) to large sled tracks which run for miles (at White Sands Missile Range, Naval Air Warfare Center - China Lake, and Sandia National Laboratories, for example). Most facilities use high-speed cinematography and can record high-speed digital data such as from strain gages. Transient measurement of the characteristics of the fuel leaving the tanks has not been made in any tests to the author's knowledge.

The second stage of fuel dispersal, atomization, is still not understood sufficiently to have

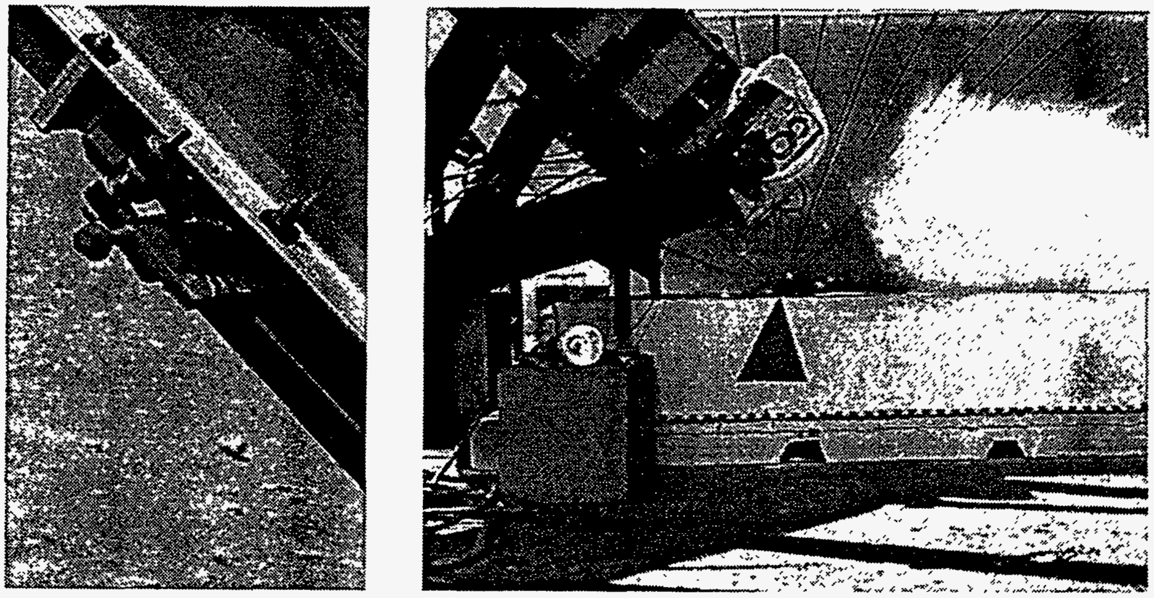

Figure 9. Example of Impact Facility for Study of the Impact Stage. Example shows liquid impact into soil for purpose of determining dispersal. Model wing chord is 0.084 m. Impact at 45°, 64 m/s. From Tieszen and Attaway, 1996.

been examined computationally at relevant scales and velocities. The principal reason for lack of an engineering computational tool (in the authors opinion) has been one of length scales. The minimum cross-sectional diameter of a wing, near the wing root, is a significant fraction of a meter. To capture fuel tank breaks and liquid flow from the tank, length scales on this order are required. At the same time, surface tension acts over length scales which are sub-millimeter (as evidenced by drop size distributions from simple pressurized atomization that range down into the hundreds of micrometers in diameter). Therefore, to be relevant to the engineering problem and to resolve the range of the surface tension forces, it is necessary to run a spectrum of at least four orders of magnitude (from sub-millimeter to meter) for each spatial dimension. In three dimensions, this would require 10^{12} grid points, a very large number by any standard, particularly for a transient, multiphase flow problem.

In many problems the length scale issue can be resolved by placing grid points densely only in regions that require it. This strategy may be employed in the present problem as well but as the fuel surface begins to breakup, the regions with high grid density requirements will quickly grow and the location of breakup will change as a function of time. As a result, to the author's knowledge, no computational tool currently directly addresses the problem of relevance. Perhaps with the arrival of the new 'teraflop' level of computing hardware, it may be possible to attempt to modify existing tools to conduct two-dimensional simulations of the breakup process. It is anticipated that fully transient problems with 10^8 grid points will be within the capability of the early teraflop level machines.

In an experimental sense, there has been substantial progress in the commercialization of drop size characterization hardware. Examples of commercial hardware vendors include Malvern[1], Insitec[2], Dantec[3], and Aerometrics[4]. Available instruments allow for the characterization of drop size and in some cases velocity. Unfortunately, they are most applicable in flow regimes near

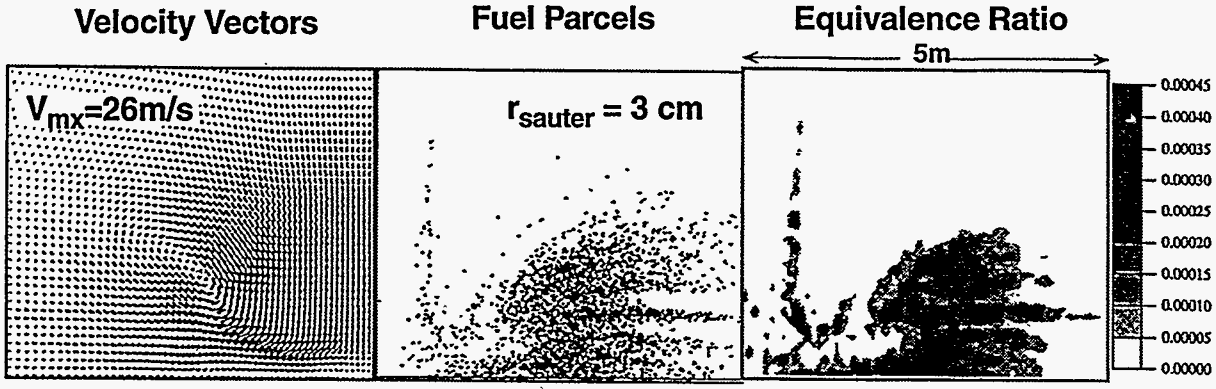

Figure 10. Example of a Numerical Simulation Tool for Study of the Interphase Momentum Exchange Stage. Modified version of the KIVA-II code (Glass, 1990).

the end of the primary breakup stage and into the interphase transfer stage. For various reasons, they have increasing trouble in the primary breakup stage. Experimental diagnostics in the primary breakup phase is still an area of active laboratory scale research and, in the opinion of the author, will be for some years to come. While engineering scale tests could be conducted in the impact facilities mentioned above, the relevance of the tests would be limited by the level of diagnostics that could be brought to bear.

The third stage of fuel dispersal, that of interphase momentum exchange, has length scale ranges even broader than the breakup stage. However, as the overall density of the fuel phase decreases relative to the gas phase, it is possible to treat the liquid phase as dispersed within the continuous gas phase. Computationally, the drops are treated as subgrid models by size classes, allowing for breakup, coalescence and interphase momentum exchange in an engineering sense. Figure 10 shows an example calculation of a dispersal of decane droplets (Glass, 1990). The computational tool is a modification of the KIVA-II code, one of several products of the T-3 group at Los Alamos National Laboratories, Los Alamos, NM that can be used for this application.

Experimentally, the interphase momentum exchange can be studied in engineering environments in the impact facilities mentioned above. Figure 11 shows a test from a medium-scale study of impact on runways in which the fragmentation of the airframe was ignored (Tieszen, 1995). Drop size diagnostics were not employed in the study but the footprint of the spray was determined by mass collection as a function of position from the impact point. The mass was collected by rapidly deploying absorbent media. All of the commercial drop size measurement devices work well in the interphase momentum exchange regime.

Tools are available for the study of ground-base flows in the final stages of dispersal prior to ignition. Computationally, commercial tools such as Flow 3D[1] can be used to track slow moving free surface flows over terrain. Experimentally, such flows can be measured at any number of

1. Malvern Instruments, Inc., 10 Southville Road, Southborough, MA 01772.
2. Insitec, Inc., 2110 Omega Road, Suite D, San Ramon, CA 94583.
3. Dantec Measurement Technology, Inc., 777 Corporate Drive, Mahwah, NJ. 07430.
4. Aerometrics, 777 N. Mary Ave., Sunnyvale, CA 94086.
1. Flow Sciences, Inc. 1325 Trinity Drive, Los Alamos, New Mexico 87544.

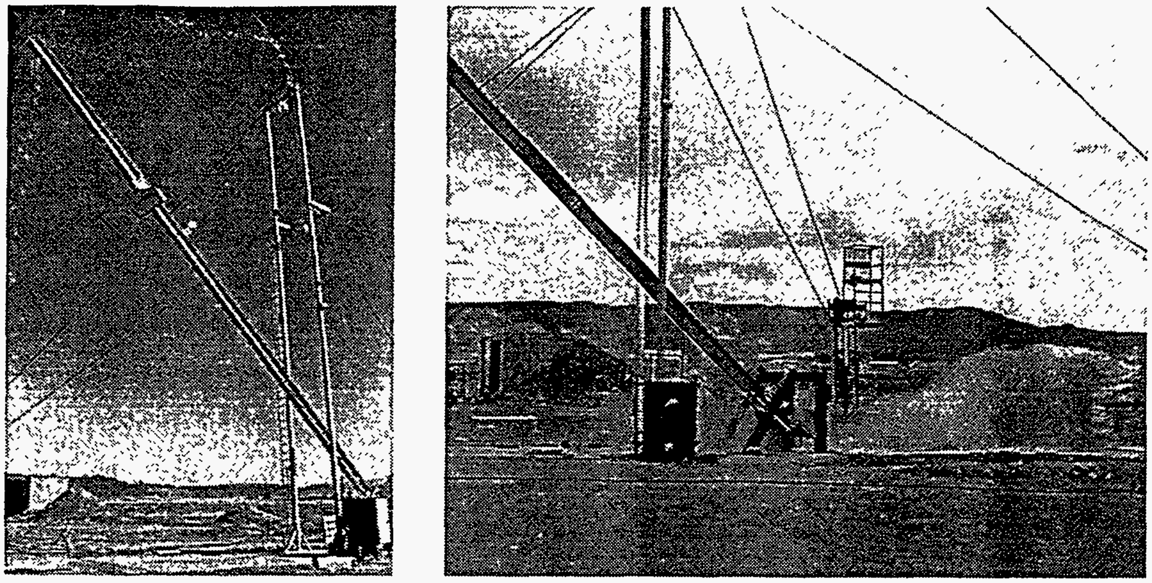

Figure 11. Example of Impact Facility for Study of the Impact Stage. Example shows liquid impact into a runway. From Tieszen and Attaway, 1996.

university hydrology laboratories at the scales required.

Post-ignition flows are very difficult to model computationally. The author is not aware of any computational fire models that have coupled free-surface flow solutions simultaneous with the fire. Computational fire models with fuel spray models are under development but to the author's knowledge have not been quantitatively demonstrated as of the time of this paper. Experimentally, numerous fire test facilities exist within the Department of Defense (all services), Department of Energy, and Department of Transportation. However, the environments are so difficult to work in that quantitative measurement of fuel dispersal characteristics during fire transients has received little to no attention.

Risk Based Decision

Given the current state of knowledge and available tools, the question may be asked, "how does one design a preventative or mitigative strategy to minimize the consequences of fuel fires in the post-crash environment in a cost-effective manner?" Effort is required in two areas to answer this question. Given an idea for a strategy, such as that pursued by the FAA for anti-misting kerosene, one must develop a design criteria for the strategy and then develop the strategy to meet the design criteria.

The development of design criteria implies that the post-crash dispersal process is sufficiently understood to permit quantitative assessment. However, from the previous sections it is obvious that while the dispersal processes in the post-crash environment are qualitatively understood, sufficient knowledge to predict the effect of a preventative strategy (say a fuel viscosity change) on the dispersal characteristics is beyond the current capability. This lack of knowledge implies that some fundamental development work in characterizing the post-crash dispersal environment is required in addition to development of a preventative strategy.

The goal of risk-based decision is to produce design criteria based on risk reduction targets (Bohn, 1992). The strategy employed is very similar to probabilistic risk assessment (PRA) methodologies. In a PRA the goal is to analyze an existing process to determine the overall risk and the dominant contributors to that risk. It employs data from three sources, historical data, deterministic subprocess models, and expert elicitation. Risk based decision differs from assessment methodologies in that the process to be studied is new. One of the strengths of risk-based decision is that it can be used to 1) assist in the definition of what physical processes need to be understood to achieve a change at the system level, 2) identify the uncertainties in the process models and sensitivity to uncertainties at a system level, 3) to conduct cost-benefit analyses to determine the cost/benefit trade-offs for a given preventative or mitigative strategy.

In risk based decision, historical data such as accident frequency can be used as input to the process (provided of course that the frequency of accidents is not modified by the process modification), but the sequence of events that occurs with the preventative or mitigative strategy implemented (say a modified-viscosity fuel) must be specified by one or more deterministic models. The deterministic models must be built in such a way that effects of the new design strategy can be propagated through the model to the consequence of interest, say passenger fire related deaths. For example, for a fuel viscosity modification, models may include one for the effect of viscosity on drop size distribution of the atomized spray, one for the effect of drop size distribution of the size and location of the combustible spray cloud formed, one for the effect of the cloud size and location on ignitability, and so forth to passenger deaths. The models must be valid over the range of crash parameters for which they will be exercised (medium and high impact regimes).

In an ideal world with perfect knowledge of all the physical processes, this type of strategy would not be difficult to implement. However, in practice it is very difficult. For example, all of the physical processes may not have been previously quantified, or may be very difficult to quantify. With these conditions, it is not possible to design deterministic models for the physical processes without doing additional fundamental research to describe the physics and such research takes considerable time and resources.

Historically, in the absence of a clear physical description of the physical processes involved, engineering judgment has been implemented based on best-available knowledge. The risk based decision process can be used to focus such expert judgment elicitation along the lines of the models that must be built in order to reach the desired result. Engineering judgment from individuals with relevant expertise can also be used to estimate, based on best-available-knowledge, what the effects are likely to be. The outcome is an initial estimate of the effects and guidance for the development of experiments and models in order to answer the questions of interest.

The result is a development path, initially tenuous due to the embodied engineering judgment, from design criteria to outcome on a system wide level. As the process becomes more understood from the data and models generated, the linkage becomes stronger and more defensible, i.e., less engineering judgment based and more science based. The process can be continuously refined to remove engineering judgment until a satisfactory level of scientific defensibility is reached. At all stages of refinement uncertainty estimates can be tracked, including uncertainty estimates from the embodied expert judgment.

In the author's opinion, this process is the most cost effective way of determining what fundamental research is necessary to complete a study, and thereby, allows the maximum amount of resources to be focussed on the development of the preventative or mitigative strategies to be employed. The risk based decision process can also be used to decide if a preventative or mitigative strategy makes sense on a cost/benefit basis once all the processes are known. To make this decision, cost estimates need to generated for research, development, and implementation, as well as, the expected savings based on the number of deaths prevented (from insurance data, for example). Relative cost/benefit analysis between multiple strategies can be conducted without the latter data.

By employing a systems strategy such as risk based decision, the effect of the preventative measure can be tracked throughout any defined process. For example, if a viscosity modification could be made to the fuel just before impact, only the post-crash environment would need be considered. If the viscosity modification was made to the fuel as the fuel was pumped onto the aircraft, then the effect of the viscosity change would have to be tracked through all processes that the fuel is used for from lubrication to combustion. In this way, the positive effects of the modification in the post-crash environment could be balanced with negative effects in other processes.

Conclusions

Much has been learned about the post-crash fuel dispersal processes in the last few decades, both from programs directed at understanding this environment and from fundamental research in fluid mechanics which has occurred over this time period. In general terms, the processes of fuel dispersal can be qualitatively described, but in many cases, quantitative prediction of effects are currently beyond our capabilities. Tools, both experimental and computational, have been developed and applied to the dispersal problem and will continue to be developed and improved with time. In order to design a preventative or mitigative strategy to lower the consequences of post-crash environments it is necessary to understand the crash process with sufficient fidelity to create quantitative design criteria for a possible mitigative or preventative strategy. Risk based decision represents an approach through which it may be possible to achieve this goal. However, quantitative description will not come easily as the post-crash environment involves a myriad of complex, coupled, and non-linear processes which are by their very nature very difficult to describe quantitatively.

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References

Ahlers, R. H. 1970. Investigation of Two Methods for Improving the Crashworthiness of Integral Fuel Tanks. FAA-RD-70-56, Atlantic City.: FAA Technical Center.

Attaway, S. W., Heinstein, M. W., Swegle, J. W. 1994. Coupling of the Smooth Particle Hydrodynamics Method with the Finite Element Method. Nuclear Engineering and Design. 150:199-205.

Bhunia, S. K. and Lienhard, J. H. 1994. Splattering During Turbulent Liquid Jet Impingement on Solid Targets. ASME Journal of Fluids Engineering. 116:338-344.

Bhunia, S. K. and Lienhard, J. H. 1994. Surface Disturbance Evolution and the Splattering of Turbulent Liquid Jets. ASME Journal of Fluids Engineering. 116:721-727.

Boeing. 1996. Statistical Summary of Commercial Jet Aircraft Accidents. Seattle, Washington.: Commercial Airplane Group.

Bohn, M. P., 1992. Decision Making Under Uncertainty: An Investigation Into the Application of Formal Decision-Making Methods to Safety Issue Decisions. SAND92-1547, Albuquer-

que, NM.: Sandia National Laboratories.
Buckson, W., Schlegel, W., and Smith, I. R. 1965. Design, Development, and Evaluation of a Crash-Resistant Fuel System Installation. FAA-ADS-27, Atlantic City, New Jersey.: FAA Technical Center.
Cline, D. D. and Koenig, L. N. 1983. The Transient Growth of an Unconfined Pool Fire. Fire Technology. 19(3):149-162.
Didden, N. and Maxworthy, T. 1982. The Viscous Spreading of Plane and Axisymmetric Gravity Currents. Journal of Fluid Mechanics. 121:347-362.
Dorofeev, S. B., Matsukov, D. I., Sidorov, v. P., Efimenko, A. A., Kochurko, A. S., Kuznetsov, M. S., Pereverzev, A. K., Avenyan, V. A, and Chaivanov, B. B. 1991. Experimental Investigation of Thermal Burning Effect from Burning Fuel-Rich Clouds. IRIS-91/3, Moscow, Russia.: Scientific Research & Development Organization Industrial Risk.
Errico, M. 1986. A Study of the Interaction of Liquid Jets with Solid Surfaces. Ph. D Thesis, Dept. of Chemical Engineering, San Diego CA.: University of California.
Faul, I. 1978. An Investigation Into Jet, Droplet and Spray Behaviour of Safety Fuels. Technical Report 78131, Farnborough UK.: Royal Aircraft Establishment.
Federal Aviation Administration. 1991. Air Safety Research Plan. Atlantic City, New Jersey.: FAA Technical Center.
Gardner, D. R. 1990. Near-Field Dispersal Modeling for Liquid Fuel-Air Explosives. SAND90-0686. Albuquerque, New Mexico.: Sandia National Laboratories.
Glass, M. W. 1990. Far Field Dispersal Modeling for Fuel-Air Explosive Devices. SAND90-0528. Albuquerque, New Mexico.: Sandia National Laboratories.
Gritzo, L.A., Nicolette, V.F, Moya, J.L., Skocypec, R.D., and Murray, D. 1995a. Wind-Induced Interaction of a Large Cylindrical Calorimeter and an Engulfing JP-8 Pool Fire. Proceedings of the Symposium on Thermal Sciences in Honor of Chancellor Chang-Lin Tien, Berkeley, CA.: University of California.
Gritzo, L.A., Nicolette, V.F., Tieszen, S.R., and Moya, J.L. 1995b. Heat Transfer to the Fuel Surface in Large Pool Fires. Transport Phenomenon in Combustion (S.H. Chan, ed).:Taylor and Francis.
Hackler, L. W., 1972. Wing Leading Edge Fuel Tank Impact Tests. FAA-RD-72-83, Atlantic City.: FAA Technical Center.
Huppert, H. E., 1982. The Propagation of Two-Dimensional and Axisymmetric Viscous Gravity Currents Over a Rigid Horizontal Surface. Journal of Fluid Mechanics. 121:43-58.
Johnson, N. B., Robertson, S. H., and Hall, D. S. 1989. Aircraft Crash Survival Design Guide Volume V - Aircraft Post-Crash Survival. USAAVSCOM TR 89-D-22E, Fort Eustis, Virginia.: U. S. Army Aviation Research & Technological Activity.
Kuchta, J. M. and Clodfelter, R. G. 1985. Aircraft Mishap Fire Pattern Investigations. AFWAL-TR-85-2057, Wright Patterson AFB, Ohio.: Air Force Wright Aeronautical Laboratories.
Lefebvre, A. H. 1989. Atomization and Sprays.:Taylor & Francis.
Lienhard, J. H., Liku, X., and Gabour, L. A. 1992. Splattering and Heat Transfer During Impingement of a Turbulent Liquid Jet. Journal of Heat Transfer. 114:362-372.
Lister, J. R. 1992. Viscous Flows Down an Inclined Plane from Point and Line Sources. Journal of Fluid Mechanics. 242:631-653.
Mahood, L., and Talley, R. L. 1982. Correlation of Flammability Test Data on Antimisting Fuels. DOT/FAA/CT-82/29, Atlantic City, New Jersey.: FAA Technical Center.
Millar, R. E., and Wilford, S. P. 1971. Simulated Crash Fire Tests as a Means of Rating Aircraft

Safety Fuels. Technical Report 71130, Farnborough, UK.: Royal Aerospace Establishment.

National Research Council. 1995. Fire- and Smoke-Resistant Interior Materials for Commercial Transport Aircraft, National Materials Advisory Board Publication NMAB-477-1, Washington, D. C.: National Academy Press.

Nicolette, V.F, Gritzo, L.A., Moya, J.L.,and Tieszen, S.R. 1995. Comparison of Large JP4- and JP8-Fueled Pool Fires. Proceedings of the International Conference on Fire Research and Engineering, Orlando, Florida.:Society of Fire Protection Engineers.

Nissley, P. M. and Heid, T. L. 1964. Structural Design for Fuel Containment Under Survivable Crash Conditions. FAA-ADS-19, Atlantic City.: FAA Technical Center.

Parikh, P., Fleeter, R., and Sarohia, V. 1983. Antimisting Fuel Breakup and Flammability. DOT/FAA/CT-82/149, Atlantic City.: FAA Technical Center.

Rockow, R. A., and Shaw, L. M. 1972. Crashworthiness of Safe Fuels. Pp. 1-13 Gas Turbine and Fluids Engineering Conference and Products Show, ASME Paper 72-GT-27, San Francisco CA.:The American Society of Mechanical Engineers.

Russell, R. A. 1971. Small-Scale Impact Tests of Crash-Safe Turbine Fuels. FAA-RD-71-49, Atlantic City.: FAA Technical Center.

Schauerman, H. P. 1971. Crash Resistant Fuel Systems Demonstration and Evaluation. FAA-RD-71-27, Atlantic City.: FAA Technical Center.

Salmon, R. F. 1981. Wing Spillage Tests Using Antimisting Fuel. FAA-CT-81-11, Atlantic City, New Jersey.: FAA Technical Center.

Shaw, L. M. 1971. Safety Evaluation of Emulsified Fuels. USAAMRDL Technical Report 71-29 Fort Eustis, Virginia.: U. S. Army Mobility Research and Development Laboratory.

Tieszen, S. R. 1995. Fuel Dispersal Modeling for Aircraft-Runway Impact Scenarios. SAND95-2529. Albuquerque, New Mexico.: Sandia National Laboratories.

Tieszen, S. R. and Attaway, S. W., 1996. Fuel Dispersal in High-Speed Aircraft/Soil Impact Scenarios. SAND96-0105. Albuquerque, New Mexico.: Sandia National Laboratories.

Tieszen, S. R., Attaway, S. W., Swegle, J. W., and Slavin, A. M. 1996a. Transient, High-Speed, Liquid Impact into Soft Soil. Computer Modeling and Simulation in Engineering. 1:79-106.

Tieszen, S. R. Nicolette, V. F., Gritzo, L. A., Holen, J. K., Murray, D., and Moya, J. L. 1996b. Vortical Structures in Pool Fires: Observation, Speculation, and Simulation. SAND96-2607. Albuquerque, New Mexico.: Sandia National Laboratories.

Tilston, J. R. 1989. The Stability of Fuel Fires. AGARD-CP-467. Farnborough, UK.: Royal Aerospace Establishment.

Wittlin, G. 1987. Fuel Containment Concepts - Transportation Category Airplanes. DOT/FAA/CT-87/18, Lockheed-California Co, Burbank, CA.: Federal Aviation Administration.

Wu, P.-K., Tseng, L.-K., and Faeth, G. M. 1992. Primary Breakup in Gas/Liquid Mixing Layers for Turbulent Liquids. Atomization and Sprays. 2(3):295-317.

Wu, P.-K. and Faeth, G. M. 1993. Aerodynamic Effects on Primary Breakup of Turbulent Liquids. Atomization and Sprays. 3(3):265-289.

Wu, P.-K. Miranda, R. F., and Faeth, G. M. 1995. Effects of Initial Flow Conditions on Primary Breakup of Nonturbulent and Turbulent Round Liquid Jets. Atomization and Sprays. 5(2):175-196.

Wu, P.-K. and Faeth, G. M. 1995. Onset and End of Drop Formation Along the Surface of Turbulent Liquid Jets in Still Gases. Physics of Fluids Series A. 7(11):2915-2917.

Yaffee, M. L. 1986. Antimisting Fuel Research and Development for Commercial Aircraft - Final Summary Report. DOT/FAA/CT-86/7, Atlantic City, New Jersey.: FAA Technical Center.