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Modeling Subsurface Multiphase Transport of JP8 During a Fuel Spill Fire

M. J. Martinez and P. I. Hopkins

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Modeling Subsurface Multiphase Transport of JP8 During a Fuel Spill Fire

M. J. Martinez and P. L. Hopkins
Engineering Sciences Center
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Abstract

A weapon safety issue concerns the effects of a fuel spill fire on a weapon system, caused by the crash of a weapon-laden aircraft and the subsequent ignition of jet fuel. Given the small fraction of pavement covering the surface of the earth, such a crash is almost certain to occur over permeable, possibly water-wet soil. Assuming the fuel is immediately ignited, the ensuing burn will be controlled by the availability of fuel to feed the fire. The availability is in turn controlled by the competing processes of fuel seepage via gravity drainage into the soil, and vaporization of fuel near the ground surface, which creates a capillary wicking action of soil-absorbed fuel back up to the fire. The interplay of these effects can create situations resembling pool fires, in the case of minimal fuel seepage into the soil, wicking-limited fires in the case of moderate seepage of fuel with significant capillary action to wick fuel from the subsurface to the fire, and rapidly extinguished fires due to effective soil absorption of the fuel spill. This study considers the multiphase multicomponent transport of JP8 jet fuel into dry (negligible water content) and fully water-wet subsurface soil. The modeling considers isothermal fuel infiltration into the soil during a steadily burning surface pool fire and the subsequent heat-driven transport once the surface pool has been depleted by combustion and infiltration of the fuel.

Acknowledgment

This work was partially funded by the ASCI safety and LDRD programs at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

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1. Introduction

A significant weapon safety issue concerns the effects of a fuel spill fire on a weapon system, caused by the crash of a weapon-laden aircraft or tanker truck and the subsequent ignition of jet fuel. Given the small fraction of pavement covering the surface of the earth, such a crash is almost certain to occur over permeable, possibly water-wet soil. Assuming the fuel is immediately ignited, the ensuing burn will be controlled by the availability of fuel to feed the fire. The availability is in turn controlled by the competing processes of fuel seepage via gravity and capillary pressure into the soil, and vaporization of fuel near the ground surface, which creates a capillary wicking action of soil-absorbed fuel back up to the fire. The interplay of these effects can create situations resembling pool fires, in the case of minimal fuel seepage into the soil, wicking-limited fires in the case of moderate seepage of fuel with significant capillary action to wick fuel from the subsurface to the fire, and rapidly extinguished fires due to effective soil absorption of the fuel spill.

The variety of possible soils and their *in-situ* moisture distribution is difficult to constrain in any rational way. In this work we consider mostly dry (zero moisture) initial conditions in the near-surface vicinity of the subsurface (where all the transport is taking place) and consider three different soil types which we believe represent a range of permeabilities that will allow significant subsurface transport effects on a surface fire. The results indicate lower permeability materials would not significantly alter the surface fire characteristics. Soils containing water and hydrocarbon fluids are typically water-wet, hence the fuel would normally be the non-wetting fluid phase. In a dry soil however, the jet fuel, JP8 in this work, would be the wetting fluid and air the non-wetting fluid. Thus, dry soil represents somewhat of a "best-case" for fuel infiltration into the soil because, as the wetting fluid, both capillary forces and gravity will drive infiltration into the subsurface. In soil containing some volume fraction of water, both the capillary action and gravity force is reduced, the latter effect due to the fact that the specific gravity of JP8 is about 0.81 at 20 C; JP8 is an LNAPL (light non-aqueous phase liquid) in the parlance of contaminant hydrology. If the soil were water-saturated (pore volume completely filled with water), the only significant driving force would be the weight of fuel pooled over the surface of the soil. Unless the pool depth is quite large, the fuel will tend to float over the water-saturated soil.

In this work we attempt to answer two related questions. Can a pool fire over permeable soil continue burning at a similar rate once the surface pool of free fuel has been depleted? The free fuel is consumed by the combustion process and by infiltration into the subsurface. A follow-on question is: if the full pool fire burn rate cannot be sustained, is it possible to sustain a fire of less intensity? If so, we will make an attempt to quantify/bound that intensity. For present purposes, this means to try to quantify the relationship between the applied radiant heat flux and the mass flux of fuel vapor from the subsurface. All of this modeling will be conducted uncoupled from a surface fire model. We assume the main effect of the surface fire on the subsurface transport is the application of a radiant heat flux over the region of the fire. In addition, we model the subsurface transport in the absence of experimental data. A testing program is planned and this work will be used as a basis for developing the experimental procedures. However, at present there is very little applicable data. So, in the absence of data and a surface fire model, we will use the multiphase multi-

component numerical model PorSalsa, described in *Martinez et al.* (1997), to provide a basis for answering the questions posed above. Appendix A provides a summary description of the mathematical model for nonisothermal two-phase, two-component flow in porous media applied in this study.

Given this setting, it must be recognized that this is an exploratory modeling effort. There is uncertainty in several aspects of the simulation. First, in the absence of a coupled pool fire model, we must propose a subsurface/surface interface model for the rate of mass transfer from the subsurface to the surface. This is a critical aspect of the problem and further is one which cannot be validated without experimental evidence. The mechanics just before the surface pool is completely absorbed is also not well-understood. A heated layer below the burning surface of a liquid pool extends 2-3 cm (*Drysdale*, 1985). The temperature at the evaporating surface is at the boiling point for the prevailing pressure and drops off to the initial liquid fuel temperature at the 2-3 cm depth. This means there is a large density gradient in this thin layer, which will be a factor in the absorption of liquid fuel at this stage. Also, there is a relation between the mass flux of fuel vapor from the subsurface and the resulting radiant heat flux, which is not directly modeled in this work. Instead we approach the problem by applying a constant value of heat flux. The resulting mass flux of JP8 vapor can be compared to the pool fire burn rate. Smaller fluxes would indicate the pool fire burn rate cannot be sustained, but the combustion may continue at a reduced rate. Comparable fluxes would indicate the fire may be sustained at a similar intensity.

1.1 Related Work

There appears to be very little quantitative work done on fires over permeable material, particularly over material similar to soils. Some of the work that has been done, (*Takeno & Hirano*, 1986, 1998) is for bead packs; these porous materials exhibit a different scale for capillary potential than would typical soils. *Suzuki et al.* (1991) performed an experiment in sand, but the emphasis was on the effect on the flame over the porous surface and no information about the nature of the interaction with the subsurface was provided.

In a series of papers (*Blackshear & Murty*, 1965, 1967; *Wood et al.*, 1971), Blackshear and co-workers considered the characteristics of liquid fuel fires from ceramic wicks and sand-filled pan burners. Both the ceramic wicks and sand-filled burners display a constant burning regime, followed by a falling burn-rate period. The authors assume this transient behavior is analogous to drying of porous materials, which display a similar behavior. Although no data is provided, Wood et al. assume that the steady burning rate corresponds to "capillary attraction" in the sand wick, and that the falling burn rate is associated with the recession of the liquid interface below the sand wick surface. These authors provided data on the burn-rate histories, the total heat flux to the sand and temperature histories at various depths in the sand-filled pan. This configuration is similar to the model studied here, except that the sand is contained in a 1.9 cm deep, 1.52 m diameter aluminum pan, such that the interstitial fuel is confined in the sand, rather than allowed to drain away as in the model considered here.

Heskestad & Dobson (1997) report experimental results for pool fires of transformer oil burning over a rock bed in a 1.2 m diameter pan, with and without drainage. For a rock

mean diameter of 23 mm, and without drainage, they observe the pool fire heat release to fall sharply once the oil level regressed 25 mm below the mean rock surface level (MRSL), defined as the horizontal level of oil where 50% of the area of the plane is broken by the rock surface. Furthermore, the fire continued to burn at a low rate (less than 10% of the steady heat release rate) for more than 3 hours, when it was extinguished manually. With drainage (regression rates of 16-26 mm/min) the decrease in heat output occurs when the oil regressed below the MRSL, and the fire self-extinguished when the oil level dropped to about the rock diameter. This porous material will be quite a bit different from most soils, with very little, if any, capillary wicking potential. Nevertheless, the results show that the fire intensity is sharply reduced once 50% of the fuel surface area is broken by the rock surface.

While there have been few studies on fuel spill fires, there has been more work done on infiltration of surface spills of NAPLs into the subsurface, particularly in connection with subsurface contamination problems. For example, one relevant study by Van Geel & Sykes (1994a, b) discusses experimental and numerical modeling results of an LNAPL spill in a variably saturated sand. This is a three-phase system consisting of water, heptane (the LNAPL) and air. The experiment was carried out in a box, 150 cm in length, 120 cm in height, and 6 cm in depth filled to a height of 114.5 cm with a well-sorted silica sand, with porosity 37.4% and vertical and horizontal permeabilities of 10 and 20 darcy¹, respectively. The spill area measured 10 cm x 6 cm in the central portion at the top of the box. An initial, nearly hydrostatic condition was established by first water-saturating the porous material, followed by setting a water-table boundary 8.7 cm from the bottom of the box. After 17.5 h of water drainage, this results in a moisture saturation of about 17% (residual water saturation) over roughly the upper 60 cm of the box; this represents the initial condition for the LNAPL spill. The heptane was applied by prescribing a constant 3 cm head of heptane over the spill area for 18.67 minutes; 2 liters of heptane were injected into the system. The heptane was allowed to infiltrate under its own head during the remainder of the experiment; data were collected to 4500 seconds. The data presented show the heptane to infiltrate as a plume below the spill area with lateral spreading of about twice the width of the spill area. At 600 s, the LNAPL has infiltrated about 20 cm, resulting in a nearly uniform 50% saturation level, i.e., the heptane does not fully saturate the available pore space, 17% of which contains liquid water at residual saturation levels. By 3000 s, the plume has penetrated roughly 50 cm, but the saturation level is non-uniform, with a peak value of about 40%. These results give an idea of the subsurface penetration of an LNAPL spill in high permeability sands. At 20 C, heptane has a specific gravity of about 0.686 and a viscosity of 0.00041 Pa-s, compared to 0.001 Pa-s for water at the same temperature. In contrast, JP8, the fuel under consideration in this report, has a specific gravity of about 0.82 and a viscosity of 0.0013 Pa-s.

1. 1 darcy = $9.87 \times 10^{-12} \text{ m}^2$.

2. Soil Properties

Three main soils were considered in this work; a few related soil types were also considered in special cases and will be presented where they arise in the ensuing discussion. The permeabilities range from 25 darcy down to 0.07 darcy. Given the short duration for infiltration of spilled fuel, we anticipate lower permeability materials will not be able to significantly absorb fuel over the durations of an assumed pool fire. Thus, we expect that for spills in lower permeability materials (less than 0.07 darcy), the subsurface transport is not significant. In a real crash, however, the material properties may be altered. This effect is considered briefly in this work.

2.1 Alluvium

This high permeability material, which we designate as alluvium, is patterned somewhat after alluvial deposits in the Albuquerque Basin as described in the hydrologic study of *Kernodle et al.* (1995). The data of Kernodle et al. show some horizontal hydraulic conductivities as high as 70 ft/day, from which we compute a 25 darcy permeability. However, since this study involves only saturated flow, no data is provided for moisture retention or relative permeabilities. We take the liberty of assuming functions for the capillary pressure and permeability models from the work of *Udell and Fitch* (1985), which describe a uniform sand material. The capillary pressure-saturation relation was obtained by fitting measured data to a cubic polynomial in gas saturation, and is given by

$$P_c = \sigma \sqrt{\frac{\phi}{k}} (1.417(1-s) - 2.12(1-s)^2 + 1.263(1-s)^3) \quad (1)$$

where σ denotes surface tension. The scaled saturation, s , is a function of the liquid saturation, S , and the material residual saturation, S_r ,

$$s = \frac{S - S_r}{1 - S_r} \quad (2)$$

Cubic functions were assumed for the relative permeabilities

$$k_{rg} = (1-s)^3 \quad k_{rl} = s^3 \quad (3)$$

The material and transport property data used to specify this material are given in Table 1 as the material designated alluvium.

2.2 Jornada Soil

The Jornada material is typical of a silty sand or soil. The material properties were described as "zone 2" in Table 3 in *Martinez et al.* (1997). Material properties are given in Table 1 of this report. The models specified for the Jornada and SNL soils (to be described next) for relative permeability and capillary pressure follow the so-called van Genuchten function (*van Genuchten*, 1978), and method of Mualem (*Mualem*, 1976), which yield

Table 1: Material and Transport Properties

Property	Symbol	Alluvium	Jornada Soil	SNL Soil
Porosity	ϕ	0.40	0.35	0.40
Permeability (m ²)	k	2.5×10^{-11}	5.6×10^{-12}	7.0×10^{-14}
Oleic Conductivity to JP8 at 20 C (cm/min)	K_s	0.89	0.20	0.0025
van-Genuchten air entry parameter (m ⁻¹)	α	NA	3.63	1.13
van-Genuchten pore size distribution parameter	β	NA	1.632	1.88
Residual liquid saturation	S_r	0.0	0.28	0.20
Grain density (kg/m ³)	ρ_s	2600	2600	2200
Heat capacity(J/kg-K)	C_s	700	700	1000
Effective thermal conductivity (W/m-K)	λ_{eff}	1.0	1.0	1.39

$$k_r(s) = \sqrt{s} \left[1 - \left(1 - s^{\frac{1}{\lambda}} \right)^{\lambda} \right]^2, \quad (4)$$

and

$$P_c(s) = \frac{\rho_l g}{\alpha} \left[s^{\frac{1}{\lambda}} - 1 \right]^{\frac{1}{\beta}}, \quad (5)$$

in which $\lambda = 1 - 1/\beta$, g is the gravitational acceleration and ρ_l is the liquid density. The relative permeability to the gas was specified as $k_{rg} = 1 - k_{rl}$ (Bixler, 1985).

2.3 SNL Soil

This data set is taken from field measurements reported by *McTigue et al.* (1993), taken at Sandia National Laboratories, in Albuquerque NM. This material consisted of well-sorted to poorly-sorted clastics that ranged in size from fine sand/silt to gravel/cobble stones. The petrophysical data in Table 1 are arithmetic means of the empirically determined values for use in the van Genuchten/Mualem models. This material has the lowest permeability

of the three materials considered, even though the porosity is similar for all three. The moisture retention and relative permeability functions are also specified by the van Genuchten and Mualem functions given by Eqns. (4) and (5).

2.4 Comparison of Capillary Pressure

The primary mechanism for supplying liquid absorbed by the soil to the surface is the wicking action generated by the porous soils. The range in the capillary pressures generated by the three soils is compared in Figure 1 (notice the abscissa is scaled saturation). There is a considerable difference in the wicking capabilities of these materials as embodied by the capillary pressure versus saturation functions presented earlier. The capillary pressure generated correlates inversely with the intrinsic permeability. The lowest permeability material is the SNL soil, which in general can exert the largest capillary pressures. On the other hand, the high permeability alluvium generates the smallest capillary pressures, about 20 kPa near residual saturation. This indicates the SNL soil has a much finer, and well-sorted, pore structure than does the alluvium. The latter must have generally larger pores of a more uniform size distribution, and thus higher permeability, but cannot generate as much capillary pressure. The Jornada soil falls somewhere in between.

3. Isothermal Fuel Infiltration into a 3D Crash-Generated Crater

3.1 Crater Geometry, Boundary and Initial Conditions.

In this first part of the analysis, we investigate the cold infiltration stage of the spill into a model three-dimensional crash-generated crater geometry for both a homogeneous and impact-modified material. Crater geometries resulting from scaled experiments in soil are

Figure 1 Capillary pressure as a function of liquid saturation for the soils considered in the analysis.

Figure 2 Crater geometry, outlined in white, and permeability ($\log_{10}(k)$, m^2) distribution for the heterogeneous sand/gravel material.

discussed in *Tieszen & Attaway* (1996). The model crater geometry used in this work is depicted in section in Figure 2. (The distribution of permeability shown in the figure is discussed in a description of the impact-modified material in section 3.3 on page 17.) The full computational model is 1.3 m in depth below the undisturbed upper surface, and includes a plan area ($x \times y$) of $2.4 \times 2.1 \text{ m}^2$. The depth to the lowest part of the crater is 0.40 m below the upper surface. The mesh spacing is a uniform 5 cm in each coordinate direction.

The infiltration of liquid JP8 from the crater into the soil is modeled by applying a liquid-saturated condition on the crater surface. Other boundaries are specified as no-flow boundaries for the fuel.

3.2 JP8 Fuel Infiltration into Homogeneous Soil

Table 1 indicates that of the three basic materials to be studied, the alluvium has the highest permeability and therefore the greatest potential to absorb fuel. Accordingly, we model the infiltration of JP8 into homogenous alluvium as the soil underlying the crater. The saturation distribution in this material depicted in Figure 3a indicates the extent of fuel infiltration after 10 minutes. The figure indicates a significant amount of fuel absorption into the soil. The fuel volume absorbed is roughly 0.6 m^3 (about 158 gal.) or about 485 kg for a liquid density of 808 kg/m^3 . Figure 4 (left figure), which depicts the saturation distribution along a vertical profile, indicates the fuel has infiltrated about 50 cm below the lowest

point in the crater. The vertical profile is located at the center of the plan area and intercepts the deepest part of the crater. The ordinate measures distance from the bottom of the mesh.

Figure 3 Liquid fuel saturation distribution from 3D crater into (a) homogeneous alluvium at 10 minutes, and (b) heterogeneous sand/gravel at 5 minutes. The slice plane in (b) depicts the heterogeneous distribution of absorbed fuel in the undisturbed layer.

Figure 4 Vertical (left) and horizontal (right) profiles of JP8 fuel saturation in the homogeneous alluvium (black) at 10 minutes and heterogeneous sand (red) at 5 minutes. See text for location of profiles.

3.3 Infiltration into Impact-Modified Heterogeneous Material

It seems reasonable that the crash which generates the crater may create a “disturbed zone” in the adjoining porous material. The exact nature of this disturbed zone poses a complication which is beyond the scope of this work. We will only attempt to address the crash-disturbed material beneath the crater by posing a vertically stacked, two-layer model (Figure 2). The underlying layer, which comprises the lower 0.5 meters of the mesh, is designated as the undisturbed material with hydrologic properties similar to a sand/gravel system (see, for example, Table 2.2 of *Freeze & Cherry, 1979*). The remainder is the disturbed zone, which includes the crater. Both materials will be modeled as fully heterogeneous, by specifying random distributions of their permeability and porosity. The random distribution of permeability ($\log_{10}(k)$, k in m^2) is shown in Figure 2. The statistics for the random distribution are given in Table 2. The disturbed material is assumed to have resulted in enhanced permeability, typical of a rubblized gravel system. The range of permeability and porosity are noticeably higher than the underlying material.

Table 2: Heterogeneous Hydrologic Data

	ϕ_{max}	ϕ_{min}	$k_{max} (\text{m}^2)$	$k_{min} (\text{m}^2)$
Disturbed zone	0.5	0.4	5×10^{-10}	1×10^{-12}
Undisturbed sand/gravel	0.4	0.3	1×10^{-11}	5×10^{-14}

Figure 3b depicts the fuel saturation distribution in the heterogeneous sand/gravel system. The lower permeability in the underlying layer causes the infiltrating fuel to pool at the interface with the undisturbed layer. The figure indicates the region between the crater surface and the undisturbed material is saturated with fuel at 5 minutes for this very high permeability gravel system. The underlying layer has the effect of trapping the fuel in the disturbed zone, at closer proximity to the crater surface which may allow the absorbed fuel to be burned by the surface fire, if the wicking action of the disturbed region is able to supply enough fuel. The slice plane in Figure 3b, located just below the top of the undisturbed layer, illustrates the heterogeneous nature of the infiltration process. The horizontal profile in Figure 4 also shows the variability in the saturation in the heterogeneous material in contrast to the homogeneous alluvium. The horizontal profile is taken along a line parallel to the x -axis, located 0.5 m from the bottom, and bisecting the y -axis of the mesh. The heterogeneous permeability and porosity fields are reflected in the horizontal profile for the heterogeneous sand, showing a high degree of local variability along this profile. Even so, the heterogeneity does not significantly impact the infiltration of fuel on the scale of the crater. The random heterogeneity distribution is restricted to the scale of the mesh (5 cm mesh spacing), and the heterogeneity impacts the saturation distribution significantly on this scale, as depicted in Figure 3b, and in the horizontal profile of Figure 4. However, on the larger scale of the crater (i.e., many mesh spacings), the distribution of liquid fuel is not much affected when compared to the saturation field depicted for the alluvium. The variability of the fuel saturation is restricted to the same scale as the random distribution of the soil properties.

Of course, this is but one realization of heterogeneity that may be encountered in subsurface geologic materials; myriad other features could significantly impact the resulting distribution of absorbed fuel. Larger, more extensive scale heterogeneities, such as fractures, wormholes, etc. could result in much different distributions, with much of the fuel draining rapidly away from the the crater surface, and therefore away from the fire where it could serve as additional fuel to sustain the fire. Obviously, if the fuel drains away, the fire will cease once the free liquid in the crater is absorbed by the soil. Also, as depicted in Figure 3, a lower permeability region below the crater can cause the absorbed fuel to pool near the crater surface where it could conceivably be wicked back out to supply fuel, albeit perhaps at a much reduced rate.

4. 2D Heat-Driven Multiphase Transport Subsequent to Pool Infiltration

In this section we examine the heat-driven subsurface transport of fuel (liquid and vapor) and air in the soils described in Section 2 due to an applied radiant heat flux. Appendix A provides a summary of the mathematical model describing this transport, see Martinez et al., 1997 for more detail. We will focus on the nonisothermal two-phase transport and simplify the geometry of the spill. The mesh considered here straddles the edge of the spill on the surface allowing an opportunity to consider edge effects on the transport. In this simplified geometry, the transport closer to the center of the fire would be one-dimensional, which is approximated by the left-hand-side of the present 2D model (see Figure 5).

The oleic conductivities, given in Table 1, indicate which materials may be able to provide sufficient fuel to feed the surface fire. The main mechanism for supplying the surface with fuel is the wicking action for lifting liquid JP8 to the surface where it can be vaporized to provide fuel for surface combustion. Owing to the heat-induced pressurization near the surface, the gases will be driven away from the drying front, both up to the surface, which we expect to be very nearly at atmospheric pressure, as well as downward away from the surface. Thus, materials for which the oleic conductivity is less than the pool fire burn rate are unlikely to be able to sustain that rate of wicking, unless there exists very large liquid gradients, which occur only briefly near the surface during the dryout period. Since the burn rate is about 0.5 cm/min, Table 1 shows that only the alluvium has a larger oleic conductivity. One might expect the other two materials will not be able to sustain a large enough supply of subsurface liquid JP8 to the surface to maintain a vigorous fire. This bears out in the simulations to follow, although it appears that neither of the materials can sustain high enough fluxes for very long.

4.1 Boundary and Initial Conditions

The 2D computations were performed on a uniform grid measuring 1m in width by 1m depth. A schematic of the geometry for this series of simulations is shown in Figure 5. This configuration is meant to represent the edge of a more extensive spill; the spill area in the model is over a half-meter on the surface. The vertical sides are modeled as symmetry boundaries. Initially the material is devoid of liquid (except for a very small residual value which was included for numerical reasons) and the void space is occupied by air at a uniform temperature of 20 °C and in static equilibrium in a gravity field. During the simulations, the bottom boundary is maintained at the initial values of temperature and pressure.

As discussed earlier, the simulation is modeled in two stages, a cold-fuel infiltration stage followed by a heat-driven transport stage which models the effects of a surface fire on the subsurface transport. The infiltration stage is modeled by specifying the spill area as saturated with liquid JP8 fuel over the infiltration time. Ambient pressure conditions are specified on the surface outside the spill area. This allows the air displaced by the liquid fuel to exit the subsurface.

Figure 5 Schematic representation of the geometry for the 2D transport simulations. Coordinates are given in meters.

The solution at the end of the infiltration stage is applied as an initial condition for the heat-driven stage. The heat-driven stage is modeled by applying a uniform heat flux over the spill area, where the pool fire is assumed to continue burning. A reduced heat flux is also applied over the remainder of the upper surface to account for radiant heat flux from the fire to its surroundings. The boundary condition for modeling the mass flux of fuel ($\dot{m}_f$) from the subsurface to the fire is specified as,

$$\dot{m}_f = \frac{\rho_g Y_{fg} k_{rg}}{\mu_g} k \left(\frac{P - P_{atm}}{\delta} \right), \quad (6)$$

where ρ_g is the gas mixture density, Y_{fg} is the mass fraction of JP8 vapor in the gas, μ_g is the mass-fraction-weighted gas mixture viscosity, P is the pressure, P_{atm} is the ambient surface pressure, and δ is a “boundary layer” length parameter equal to the mesh spacing in the simulations. This formula is applied such that only a flux *out* of the subsurface is allowed. This form for the mass flux boundary condition is driven by the pressure in the subsurface just below the upper surface. As heat is applied to the surface, the fluids and porous material heat up causing the pressure (P) to increase. As the pressure increases, this formula controls the amount of fuel in the form of vapor that is driven to the fire. This form is modeled after the Darcy law for flow in porous media. It contains the fuel vapor density ($\rho_g Y_{fg}$) as a multiplying factor so that the flux reflects the mass fraction of the gas that is fuel vapor. We also considered a model based on a diffusion boundary layer, typical of mass transfer phenomena. However, given the very high heat fluxes on the surface and the expected pressure rise, diffusion alone does not seem to properly describe the driving forces. A sample calculation with the diffusion boundary layer model confirmed that the diffusion is unable to provide a high enough mass flux to sustain a surface fire of JP8.

Away from the spill area, we expect roughly ambient concentrations of air, so the boundary condition for the air component is,

$$\dot{m}_{air} = h_{air}(P_a - P_{a,ref}), \quad (7)$$

where, unless otherwise stated, we used $h_{air} = 5.6 \times 10^{-6}$ kg/Pa-m²-s, and $P_{a,ref} = 100.102$ kPa.

4.2 Isothermal Fuel Infiltration During Pool Fire

It was assumed that the spill volume was such as to stand 20 cm in height under quiescent conditions. Using a pool recession rate ($\dot{r}$) due to combustion of about 4.7 mm/min (This burn rate is typical of fuel oils for pool diameters greater than 1 m, see Figure 5.1 of *Drysdale*, 1985), corresponding to 0.063 kg/m²-s with a liquid density for JP8 of about 800 kg/m³ at 20 C, an approximate but comparable infiltration time for each of the soils can be estimated from the following formula,

$$t_{infil} = \frac{L_f}{\dot{r} + K_s}, \quad (8)$$

where L_f (≈ 20 cm) is the undisturbed fuel depth, and $K_s = (\rho g k)/\mu$ is the so-called saturated conductivity of the fuel (in m/sec), which may be thought of as the rate of gravity drainage at fuel saturated conditions. The formula predicts the 20 cm of fuel will be consumed via combustion and seepage in 15, 30 and 40 minutes for the alluvium, Jornada and SNL soils, respectively. The simulation results are similar, but not the same since the formula does not take into account the capillary forces, which are significant early in the infiltration process. In the alluvium, for which $K_s/\dot{r} \approx 2$, the 20 cm of fuel is consumed via combustion and seepage in about 10 minutes, whereas the processes requires 30 minutes for the Jornada soil and about 40 minutes for the SNL soil. Note that the cold infiltration for SNL soil was only allowed to proceed for 30 minutes, which we arbitrarily took as the maximum time for the pool fire burn prior to pool fuel depletion above the permeable soil. This underestimates the infiltration volume in the SNL soil by about 18% (if it was allowed to infiltrate for 40 minutes), compared to the other two soils.

Figure 6 shows the extent of infiltration of JP8 into the three different soils under the conditions just described. The amount of fuel absorbed by the soil correlates with the material permeability. The SNL soil has the lowest permeability and absorbs only 1.8 cm (equivalent standing liquid depth) in 30 minutes, during which time the pool fire consumes the remainder. In contrast the Jornada soil absorbs about 7.6 cm, of the original 20 cm of

Figure 6 Extent of JP8 infiltration into a) SNL soil and b) Jornada soil, both at 30 minutes, and c) Alluvium at 10 minutes. The equivalent standing liquid depths of JP8 are 1.8, 7.6 and 15 cm, respectively. The computational domain measures 1 m on a side.

fuel, while the high permeability alluvium takes up about 15 cm in 10 minutes, leaving only 5 cm of fuel to be consumed by the pool fire. These results emphasize the significance of the soil permeability in the duration of a fuel spill pool fire in general. The high permeability alluvium is able to absorb the spilled fuel at roughly 3 times the combustion rate via the combined effects of gravity drainage and capillary action. As a result, only about 1/4 of the original fuel is actually available for pool fire combustion, the remainder having been absorbed by the soil. In the following, we will investigate how much of this absorbed fuel might yet be consumed by the fire, via a heat induced wicking action of subsurface fuel to the surface. Ignoring any heating effects for the moment, Figure 7 shows the distribution of liquid fuel and gas pressure in the Alluvium at about 30 minutes due solely to gravity drainage following the 10 minute fuel infiltration period. The centroid of liquid fuel is roughly 50 cm below the surface and the entire plume is seen to have dispersed due to capillary wicking effects. Notice that the liquid plume induces a higher pressure below as it displaces the gas, including pushing gas out the bottom of the domain.

The motion of the plume also creates a low pressure region slightly behind the advancing plume, which draws gas to this region, including gas from the surface as indicated by the gas velocity vector field depicted in the figure.

4.3 Transport at 10kW/m^2 Heat Flux

We model the subsurface heating due to the assumed surface fire by applying a constant heat flux of 10 kW/m^2 over 50 cm on the left-hand-side of the surface, i.e., over the spill

Figure 7 Liquid fuel saturation (color), pressure (contour lines) and gas Darcy velocity vector field at 30 minutes due to isothermal gravity drainage following a 10 minute fuel infiltration period.

area. Over the remaining 50 cm we apply a reduced flux of 2 kW/m^2 to model a reduction in the heat flux for areas further from the fire. Over the spill area we assume no flow of air, since we expect the combustion to deplete the oxidant. Over the remainder of the surface we apply a mixed boundary flux of air (Eq. (7)) to maintain about 1 atm pressure. Over the spill area we apply the mass flux boundary condition given in Eq. (6) to the JP8.

The 10 kW/m^2 heat flux is on the low side of some recent measurements of heat transfer to the fuel surface in large pool fires Gritzo et al. (1996). This value is more characteristic of the measurements in the 1 foot diameter fires studied by Hamins et al., (1994). However, as we shall see, the results from the 10 kW/m^2 heat flux suggest higher heat fluxes would not alter our final conclusions in relation to the objectives of this work as outlined earlier in the introduction.

The separation of the simulation into a cold infiltration stage followed by the application of the heat flux is an approximation. As shown in Figure 5.5 of Drysdale (1985), during steady burning of a liquid pool, the heat penetrates about 2-3 cm below the surface. The temperature distribution in this layer follows roughly an exponential curve in space joining the boiling temperature at the burning surface to the initial liquid fuel temperature a few cm below the surface. By assuming a cold infiltration stage, this feature is ignored in the present calculations, and so an artificial heat induction time will be present in the calculations. With this in mind, the simulation results we want to focus on begin after the induction period, when the surface temperature has reached the boiling point at the prevailing pressure. The vapor pressure for JP8 (Figure 8, curve fit from data in Fig. 20 of Handbook of Aviation Fuels, *Coordinating Research Council*, 1983) is quite low at ambient temperatures and indicates boiling at about 195°C .

In the following we discuss the results of simulations with the foregoing boundary conditions on the three materials. There are both similarities and differences in the results owing to the contrast in properties.

Figure 8 Vapor pressure for JP8.

4.3.1 Alluvium

We begin by discussing the results obtained in the alluvium, which represents the most permeable soil considered. Figure 9 shows vertical profiles of pressure, temperature and JP8 liquid saturation on the left-side symmetry boundary of the mesh, $x=0$. The profiles at 10 minutes show the state at the end of the cold infiltration period and the beginning of the heating period. At 16 minutes, the surface experiences dryout, i.e., the liquid JP8 has all been evaporated and only (superheated) gas is left. The dryout on the spill area actually commences roughly at about 45 cm from the left-hand-side, and first occurs at about 14 minutes. Thus it takes only about 2 minutes for the drying front to move across the top surface. As depicted in Figure 10, the dryout first appears near the edge of the spill area because this is where the drainage of liquid away from the surface is greatest. Besides downward gravity drainage, there is an additional lateral wicking of liquid from underneath the spill to the right in this case, where no fuel was introduced. At dryout, the temperature is close to the atmospheric boiling temperature for JP8, see Figure 8 (The pressure is only slightly higher than atmospheric.). At 25 minutes the drying front has progressed about 1 cm below the surface, the temperature is nearly 400 C, and the pressure is still only at about 101.1 kPa. These conditions result in a small superheated zone of about 1 cm thickness adjacent to the surface which contains only superheated gas. The solution profile for the saturation at 25 minutes indicates only about 6% of the liquid fuel in place at 30 minutes has been burned. This corresponds to about 7 kg per unit area, which is only

Figure 9 Profiles on the symmetry boundary ($x=0$) of the Alluvium for a 10 kW/m^2 heat flux. (black - 10 min.; red - 16 min.; green - 25 min.)

Figure 10 Distribution of liquid JP8 saturation and gas velocity field in the alluvium at 15 (left) and 25 (right) minutes.

about 1/3 of the burn rate, 22.7 kg per unit area. Along this vertical line very little of the fuel has been lost to the surface; most has drained away

The temperature and liquid JP8 saturation histories at the left-side symmetry point (upper left corner) on the surface are compared for all three materials in Figure 11. All show a very rapid surface dryout, particularly the alluvium. This material drains relatively quickly, so that the liquid fuel is more rapidly depleted near the surface, relative to the other materials. The increase in slope of the temperature curves marks the onset of dryout in the material. The temperature histories illustrate the time delay in heating of the porous material mentioned earlier. To reiterate, at the onset of application of the radiant heat flux, the system is assumed to be at the ambient temperature of 20 °C. However, it is known that the thermal wave in a pool fire penetrates a few cm below the burning surface.

Figure 11 Comparison of temperature and liquid fuel saturation on the symmetry boundary ($x=0$) for a constant 10kW/m^2 heat flux. (black - alluvium; red - Jornada Soil; green - SNL soil)

Figure 12 Spatial distribution of fuel mass flux to the surface and fuel saturation over times spanning the dryout phase of the upper surface of the Jornada soil for a 10kW/m^2 heat flux. Curve labels depict time in minutes.

4.3.2 Jornada Soil

To get an idea of the spatial variability and timescales for surface dryout, Figure 12 shows the distribution of mass flux over the spill area just before, during, and after the onset of dryout at the surface. By dryout, we refer to the complete evaporation of any liquid JP8 at some location, leaving only a superheated gas mixture composed of JP8 vapor and air. The figure also shows the distribution of liquid fuel saturation over the entire upper surface of the computational region. Dryout is indicated when the liquid fuel saturation goes to zero. Notice the rapid dryout that takes place starting at about 45 cm from the left-hand-side. At this location, the fuel saturation goes from about 60% to zero (dryout) in about 30 seconds. This is due to the high heat flux and also due to the fact that the relative permeability goes to zero at residual saturation, which is at 28%. Thus, once the fuel saturation goes to near residual, the permeability to the liquid fuel goes to zero such that wicking of the immediately surrounding fuel is no longer possible. The figure also indicates the entire upper surface dries out over a period of roughly 1 minute. Thereafter the liquid fuel to the right of the heat zone ($x > 0.5$ m) is depleted at a much slower rate, as it is wicked to the dryout region and drains due to gravity.

The main feature to notice from Figure 12 is that the mass flux of fuel to the surface is comparable to the pool fire burn rate ($0.063\text{ kg/m}^2\text{s}$) only during the rapid dryout period. There is a high pressure wave that follows the drying fronts associated with the transition from two-phase to single phase gas conditions. This feature is also manifested in the mass flux rate and can be clearly seen on the curves for 34 and 34.5 minutes, showing extrema at the drying fronts. Otherwise, the mass flux of fuel is generally lower than the pool fire burn rate ($0.063\text{ kg/m}^2\text{s}$). For example, the mass flux of fuel is $0.02\text{ kg/m}^2\text{s}$ for the curve at 41 minutes, which is about one-third the pool fire burn rate. The mass flux decreases further as the drying front penetrates the soil and thereby reduces the effectiveness of the wicking action to supply fuel to the drying front for evaporation.

Figure 13 Comparison of fuel mass flux history on the symmetry boundary for a constant 10 kW/m^2 heat flux. (black - alluvium; red - Jornada Soil; green - SNL soil)

4.3.3 Mass Flux Histories at 10 kW/m^2

The fuel mass flux histories on the symmetry boundary (i.e., the upper left corner) are compared in Figure 13 for the three different soils, all for a constant 10 kW/m^2 heat flux. The time offset for the alluvium corresponds to the application of heat flux after 10 minutes, compared to 30 minutes for the other two soils. Recalling that the pool fire burn rate is about $0.063 \text{ kg/m}^2\text{s}$, the figure shows that the present simulations indicate this level of fuel mass flux to the surface for only a very short time period. The mass flux in the Alluvium sustains this level for only about 2 minutes, the Jornada soil for less time, and the low-permeability SNL soil attains this level for no more than a few seconds. It should be noted that not every time plane of data was output for visualization, so the peak values are probably not the true peak values in the simulation. The rapid decrease in mass flux for all three materials corresponds to dryout of liquid fuel on the surface. The mass flux histories for the alluvium are only slightly higher than for the Jornada soil even though the former has a factor of 4.5 higher permeability; this indicates insensitivity to the material permeability for values greater than about 6 darcy. The lower permeability of the SNL soil results in generally lower mass fluxes.

These results indicate that once the free liquid pool is absorbed by the soil, the fire can continue to burn at the pool fire burn rate, $0.063 \text{ kg/m}^2\text{s}$, for only a minute or two before the soil surface dries out and a sufficient flux of fuel can no longer be supplied. Once dryout has occurred, the flux of fuel expelled from the subsurface is much reduced, but greater than zero. This indicates a lower level of combustion may still take place.

The (damped) oscillatory history of the mass flux for the SNL soil is a numerical artifact. The histories for the other materials also display the beginning of a new cycle. A time history of the pressure at the same location will display a similar behavior. The peaks correspond to dryout at a particular node point. Prior to dryout, the pressure at a node is

controlled by the temperature at the same node via the saturation vapor pressure relation (the partial air pressure is also a factor, but mostly the pressure is controlled by the vapor pressure of JP8). Following dryout, temperature and pressure are independent, and the pressure relaxes to a value lower than the nearest two-phase node, whose pressure is controlled by the saturated vapor pressure, but now at a lower temperature since the node is deeper into the soil. This is why subsequent peaks in mass flux are lower.

4.4 Simulation of Lower Intensity Combustion

Previous simulations were performed at a time-independent heat flux of 10 kW/m^2 . In a more realistic model, one would assume the radiant heat flux is coupled to the subsurface fuel flux supplied. Engineering models for this coupling typically specify a linear relationship, see for example section 4.4 of *Drysdale* (1985) and section III of Fernandez-Pello in *Cox* (1995).

4.4.1 Jornada and Alluvium at 2 kW/m^2 Heat Flux

An approximate model to investigate the heat-reduction effect was developed by reducing the heat flux from 10 kW/m^2 to 2 kW/m^2 at 41.5 minutes into the simulation of the Jornada soil. Beyond this time the mass flux in the 10 kW/m^2 simulation has dropped to roughly 10% of the burn rate. This reduced value of heat flux is somewhat arbitrary, but is roughly 10% of some large pool fires conducted at SNL. To perform this simulation of lower intensity combustion, the 10 kW/m^2 simulation at 41.5 minutes was used as an initial condition to the 2 kW/m^2 simulation. The time history of the mass flux at the symmetry boundary is compared in Figure 14 to the fuel mass flux history from the 10 kW/m^2 simulation, with some time overlap. The simulation is performed to a total time of 2 hours, during which time the mass flux drops off to about $0.001 \text{ kg/m}^2\text{s}$, roughly another factor of 10. In a fully coupled model, one would expect the mass flux to drop off even faster since the heat flux would also be decreasing.

Figure 14 Mass flux history at the symmetry boundary in Jornada soil for 10 kW/m^2 (red curve) and 2 kW/m^2 (black curve) heat fluxes.

Figure 15 Mass flux history at the symmetry boundary in alluvium for 10 kW/m² (black curve) followed by 2 kW/m² (green curve) heat flux beginning at 18 minutes.

A similar simulation in the alluvium was also performed. In this case the heat flux was reduced from 10 kW/m² to 2 kW/m² at 18 minutes into the simulation of the alluvium, when the mass flux is about 0.014 kg/m²s. The mass flux history at the symmetry boundary is shown in Figure 15 as the green curve. The black curve is the mass flux with a time-independent application of 10 kW/m². The solution for 10 kW/m² serves as the initial condition at 18 minutes for dropping the heat flux to 2 kW/m². The figure shows the mass flux decreases immediately after 18 minutes only to increase to a local maximum at 24 minutes before finally going to zero just before 30 minutes. Thus, this simulation indicates the combustion would self-extinguish at about 30 minutes into the simulation. The increase in mass flux near 24 minutes is due to temperature-dependent viscosity. The viscosity of air and JP8 vapor both increase with temperature, typical of gases. With the decrease in heat flux, as the gases cool down they become less viscous. The viscosity decreases faster with temperature than the corresponding decrease in pressure, which results in a greater mass flux according to the formula in Eq. (6). The self-extinguishment occurs because this material is not able to wick sufficient liquid fuel to maintain the vapor flux to the surface. The high permeability of this material allows the fuel to drain rather quickly. This depletes available fuel from the surface where it could be wicked to feed the combustion. The heating is sufficient to maintain an elevated pressure in the porous material above the ambient external pressure. This pressure difference drives gas out of the subsurface, but the mass fraction of JP8 vapor continually decreases because the outflow entrains increasing amounts of air as the temperature decreases, and because the liquid is draining away via gravity.

The mass fraction history of JP8 vapor at the surface symmetry boundary is shown in Figure 16, together with the histories in the two other materials. Recall that the heat flux was dropped from 10 kW/m² to 2 kW/m² at 18 and 41.5 minutes for the alluvium and Jornada soils, respectively, while for the SNL soil the heat flux was dropped to 1 kW/m² at 52 min-

Figure 16 JP8 vapor mass fraction history at the symmetry boundary due to time-variable heat flux in alluvium (black), Jornada (red) and SNL (green) soils. The heat flux change is from 10 kW/m^2 to 2 kW/m^2 in the alluvium and Jornada soils, and 10 kW/m^2 to 1 kW/m^2 in the SNL soil.

utes (This problem will be discussed next.). As discussed previously, the vapor fraction goes to zero in the alluvium, and generally decreases in the other two materials as well.

4.4.2 SNL Soil at 1 kW/m^2 Heat Flux

The SNL soil produces a much smaller mass flux at the 10 kW/m^2 heat flux than the other materials. Consequently, the low intensity combustion phase of the simulation is performed by reducing the heat flux to 1 kW/m^2 at 52 minutes. In Figure 17 we show vertical profiles of the solution variables at the symmetry boundary (left-hand-side) over the upper 20 cm of the subsurface. Again, these solutions are for a 10 kW/m^2 heat flux applied from 30 to 52 minutes, followed by a 1 kW/m^2 heat flux thereafter. Thus the figure depicts two profiles at the 10 kW/m^2 heat flux and two at the 1 kW/m^2 heat flux.

At 30 minutes, which marks the end of the cold infiltration stage and the start of the 10 kW/m^2 heat flux application, the temperature is at 20 C and the JP8 fuel has infiltrated about 6 cm into the subsurface. Surface dryout occurs at about 43.5 minutes, as indicated by the liquid saturation profiles. At dryout, the surface temperature is about 230 C (The atmospheric boiling temperature is roughly 195 C .), the pressure is almost 115 kPa, the corresponding (thermodynamic) saturation pressure, and the vapor mass fraction of JP8 is nearly unity. The drying front has progressed to about 2 cm at 60 minutes, and the temperature has cooled back to about 230 C after an excursion to about 325 C at 52 minutes (see Figure 11), just before reducing the heat flux. The region between the drying front and the surface is in a superheated all-gas state, consisting of JP8 vapor and air. The pressure attains a maximum at the drying front, where the pressure is controlled by the saturation pressure for the prevailing temperature. This creates a pressure gradient which drives gas (JP8 vapor and air) to the surface as well as downward, away from the drying front. By 2

Figure 17 Vertical profiles at the symmetry boundary in SNL soil for 10 kW/m² from 30 - 52 minutes, followed by 1 kW/m² heat flux to 2 hours.

hours, the drying front has progressed only about 1 cm further, although gravity drainage has moved the leading edge of the liquid blob to about 10 cm below the surface. The thermal pulse has penetrated to about 25 cm at 2 hours. The mass fraction of JP8 vapor at the surface decreases with time following dryout at the surface, falling to a value of about 40% at 2 hours. About 36% of the liquid fuel introduced during the infiltration remains in the subsurface at 2 hours.

The mass flux produced in the present simulation (reduction to 1 kW/m² heat flux) is compared with the flux attained with the 10 kW/m² heat flux in Figure 18. The reduction in heat flux results in a rapid reduction of mass flux to about 70 minutes. Thereafter the mass flux attains a quasi-steady though slowly decreasing value of roughly 0.00023 kg/m²s to 2 hours. The mass flux history plot (Figure 18) shows the mass flux attains a nearly quasi-steady distribution during this time period. During this quasi-steady period there is a close balance between the rate of evaporation of fuel and the wicking of liquid from below via capillary forces. This cannot be sustained due to the finite amount of fuel and gravity drainage. Note that the very low value of mass flux for 1 kW/m² heat flux is not consistent with a linear reduction from say a 20 kW/m² (0.063 kg/m²s) fire. Hence, we would assume the fire would have extinguished itself well before 2 hours. However, this simulation

Figure 18 Mass flux history in SNL soil for a 10 kW/m^2 heat flux (green) curve and a 1 kW/m^2 heat flux (black) beginning at 52 minutes, using the 10 kW/m^2 heat flux solution as initial condition.

does illustrate the extraction rate of liquid fuel absorbed in SNL soil if a steady 1 kW/m^2 heat flux were applied on the surface.

4.5 Discussion

The multiphase subsurface transport problem considered displays several features which inhibit a vigorous flux of fuel vapor to the surface. Once absorbed, it is difficult to heat the liquid fuel residing in the subsurface since the system is heated from above. Also, the heat flux on the surface increases the pressure at the surface, thereby providing the mechanism for driving fuel vapor to the fire, but this pressure gradient also acts to push vapors deeper into the soil, thus driving away part of the vaporized fuel.

Basically, gravity drainage and to a certain extent the heat flux act to inhibit extraction of fuel from the subsurface to the surface. It is only the wicking action that can keep the top surface fuel-wet, much like the wick in a candle draws wax from the melt pool to the flame. A good analogue is the oil lamp. If the wick is extended too much, the wicking action is unable to maintain the required liquid fuel flux at the flame, and the flame will go out. If the wick is drawn too close to the oil, a sooty, fuel-rich flame results. In the present problem, the soil takes the place of the wick, and in this case our simulations indicate the fire will go out if the upper surface dries out (i.e., liquid fuel is depleted). Our simulations confirm that the dryout time is a critical event in that fuel flux is substantially reduced thereafter. It appears to be reduced to the extent that the steady burning rate cannot be sustained. If combustion ensues, it certainly does not appear that it will be at the pool fire burn rate, but perhaps a low intensity flame. Follow-on studies should focus on establishing the relationship between the applied heat flux and the resulting mass flux of vaporized fuel.

Figure 19 Mass flux history in Jornada soil. Red: pre-heated fuel, 1 cm mesh, Eq. 6 BC; Green: no pre-heat, 1 cm mesh, Eq. 6 BC; Black symbols: same as green with 3.5 minute time offset; Blue: no pre-heat, 2 cm mesh, $h_f = 6.8 \times 10^{-5} \text{ kg/Pa} \cdot \text{m}^2 \cdot \text{s}$.

4.6 Model Verification Studies

A few model parameter variations were conducted with the Jornada and SNL soils to assess their effect on the solutions. In particular, effects of pre-heating the fuel prior to infiltration and the formulation of the mass transfer boundary condition were considered.

4.6.1 Effects of Fuel Pre-heating

The solutions given earlier were performed without accounting for some pre-heating of the liquid fuel absorbed by the permeable soil prior to applying the radiant heat flux. Since the surface fire and pool dynamics are not modeled, it is not clear how to properly model the pre-heating of fuel. In this study, the pre-heat was effected by simulating cold fuel infiltration to 1740 seconds, then injecting hot fuel ($(\dot{m}h)_{fuel} = 48 \text{ kW/m}^2$) for 60 seconds. This value of energy flux was obtained by trial-and-error and was found sufficient to raise the temperature to roughly the boiling point of JP8. Figure 19 compares the effect of pre-heating the fuel (red curve) with the solution obtained without the pre-heat (green curve). The symbols represent the same solution as the (green) non-preheated case, but with a time-offset of 3.5 minutes, showing that neglecting the pre-heat yields effectively the same mass flux history, but with a 3.5 minute time-lag. The solution with the pre-heat experiences a slightly shorter duration of high ($> 0.05 \text{ kg/m}^2 \cdot \text{s}$ say) mass flux. Since we do not have code output at each time step, the difference in peak values is probably not significant, because the true extremum may occur between the output time planes used in the figure. This study demonstrates that neglecting the pre-heat introduces a time-lag. However, since the mass flux history curves have such a definite structure, it is not difficult to account for this time lag when interpreting the solutions given previously, which did not attempt to include the pre-heat. Perhaps the best procedure is to estimate the time lag by locating the time in the unpre-heated simulations where the temperature reaches the boiling point, approximately at 195 C.

4.6.2 Effect of Mass Transfer Boundary Condition Formulation

This section discusses studies performed to evaluate the sensitivity of results to the formulation of the mass transfer boundary condition, namely the formulation of the effective mass transfer coefficient, and the grid resolution. In the Jornada soil, Figure 19 compares results obtained on a 1 and 2 cm mesh. The 2 cm mesh effectively introduces additional time lag, but a similar mass flux history otherwise when compared to the 1 cm mesh. Again, the peak mass flux is a bit less, but not significantly so for the purposes of this study; except for a time span of a few minutes, the mass flux is substantially less than the pool fire burn rate. The time lag occurs because the numerical control volumes associated with grid points on the surface in the 2 cm mesh are twice the size of the 1 cm mesh and hence will take longer to experience dryout. The solution on the 2 cm mesh was obtained using the following mass flux boundary condition

$$\dot{m}_f = h_f(P - P_{atm}), \quad (9)$$

in which $h_f = 6.8 \times 10^{-5}$ kg/Pa-m²-s (i.e., a constant). The constant value falls in the central range of the equivalent transfer coefficient values taken on during the simulation using Eq. (6). The figure shows that the mass flux history using this simpler model produces a similar result as when using Eq. (6), taking account of the time lag introduced by the coarser mesh. This indicates that these results are not overly sensitive to the exact formulation of this boundary condition.

Figure 20 also compares the effect of the formulation of the mass transfer boundary condition, this time in the SNL soil. The red curves correspond to specifying the mass transfer rate as in Eq. (9) but with $h_f = 0.8 \times 10^{-6}$ kg/Pa-m²-s, constant in time, rather than Eq. (6). This value for the effective mass transfer rate coefficient is similar to the time-averaged quantity that results from Eq. (6). The mass flux obtained with Eq. (6) is higher in peak value, and also occurs sooner, but the time histories eventually match up. The use of a constant coefficient results in lower peak vapor mass flux, but broadens the time interval of high mass flux. During this high mass flux period, the equivalent variable mass transfer coefficient given by using Eq. (6) is larger than the constant value, resulting in higher mass fluxes over a shorter time period. The smaller coefficient also results in higher pressures by restricting the transport of vaporized fuel as compared to the variable coefficient results. The temperature history is not affected as much by these differences in mass transfer coefficient. Except for a delay in the surface dryout, indicated by the rise in slope of the temperature history at 40 minutes, the temperature history is very similar for the two cases thereafter.

These results, together with the results from the Jornada soil, show that the variable formulation results in quicker response of higher intensity but shorter duration. Otherwise, the results are similar quantitatively to the constant coefficient formulation after the surface dries out.

Figure 20 Effect of surface mass transfer boundary condition in the SNL soil.

5. Isothermal Infiltration of JP8 into Water-Saturated Soils

Another bounding simulation of interest to the fuel spill problem is the infiltration of JP8 into water-saturated soil. In contrast to the JP8/air system discussed earlier, here JP8 is the nonwetting fluid in comparison to the water. Furthermore, since the specific gravity of JP8 is about 0.8, the only transport mechanism available to drive JP8 into water-saturated soil is its own standing head on the surface.

5.1 Numerical Model

This problem was modeled with PorSalsa by replacing the non-wetting air component with JP8, under restricted conditions. The implemented modifications are restricted by assuming the JP8 to be incompressible and the simulations to be isothermal. Thus the density and viscosity for JP8 at 20 C are specified as constants in the simulations. These modifications are implemented by developing a new equation of state for this pair of fluids; nothing else in the code requires modification.

5.2 Results

The simulations were performed on the 2D domain shown earlier in Figure 5. The initial condition is hydrostatic. The spill is modeled by applying an over-pressure equivalent to a standing 20 cm head of JP8 over the spill area on the surface, 1.585 kPa. This pressure (1 atm + 1.585 kPa) is maintained *throughout* the simulation; this will over-estimate the infiltration because the pressure head will actually decrease as the fuel is burned and imbibed by the soil.

The simulations were performed in the alluvium and Jornada soils. The model for relative permeability to JP8 in the Jornada material was modified from what is shown following Eq. (5), $k_{rJP8} = 1 - k_{rl}$, which is the form first used by Bixler (1985) for the nonwetting phase in a two-phase system. This may be a reasonable model in water/air systems, especially under conditions similar to classic “unsaturated flow” where the air is presumed to flow in a relatively unimpeded manner. However, for liquid/liquid systems, the relative permeability to the nonwetting phase is grossly over-estimated in comparison to available data in the literature (Fetter, 1993; Scheidegger, 1974). A better model was proposed by Parker *et al.* (1987), which is an extension of the van Genuchten model for NAPL/water systems. In this model, the relative permeability to the wetting phase (water) remains as described in Eq. (5), while the relative permeability to the non-wetting phase (JP8 in this case) is

$$k_{rn} = \sqrt{1-s} \left(1 - s^{\frac{1}{\lambda}} \right)^{2\lambda} \quad s = \frac{S - S_r}{S_s - S_r}, \quad (10)$$

where $S_s = 1 - S_{rg}$, is the maximum water saturation, and the other parameters are as defined earlier for the van Genuchten model. In these simulations, we take the maximum water saturation as unity.

Simulations of infiltration due to a constant 20 cm head of JP8 at the surface result in 4.95 and 3.6 mm (equivalent standing liquid depth) of JP8 in the alluvium and Jornada² soils, respectively. Figure 21 shows the vertical profile on the left-hand boundary of liquid JP8 saturation in the soils at 30 minutes. The figure indicates the highest saturation attained in these simulations is only 24% at the surface of the alluvium. Also shown in the figure is the saturation distribution in the sand described in Udell & Fitch (1985), which has the same characteristics as the alluvium material defined here, but with an intrinsic permeability of 1 darcy (versus 25 darcy for the alluvium). The cumulative infiltration of JP8 into the Udell sand is 0.29 mm at 30 minutes. The simulation was not run for the SNL soil, owing to the negligible infiltration that resulted in the much more permeable Udell sand. These results correlate with the soil permeabilities, which we recall to be 25, 5.6 and 1 darcy, for the alluvium, Jornada and Udell materials, respectively. However, the infiltration also depends on the functional relationships embodied in the capillary pressure and rela-

2. Using the Bixler model for the relative permeability of JP8 results in 4.9 mm of infiltration in the Jornada soil.

Figure 21 JP8 saturation distribution after 30 minutes of infiltration due to a constant 20 cm (JP8) head applied at the surface.

tive permeability functions, and so this correlation is nonlinear. Nevertheless, these are modest infiltrations when compared to the 20 cm of fuel originally available. The simulations suggest that the infiltration of JP8 into water-saturated soil could be safely ignored in a fuel spill fire model. This is quite in contrast to the case of dry (water-free) soils discussed earlier, where the infiltration effect can significantly deplete the fuel available to the fire. Basically, unless the spill volume is much larger than is modeled here, the spilled fuel will simply float on water-saturated soil until it is all burned in the fire.

6. Concluding Remarks

6.1 Infiltration

The infiltration simulations clearly illustrate the effect the material permeability can play on the overall duration of the fire for infiltration into dry soils. The high permeability alluvium absorbs about 3/4 of the fuel spill leaving only 1/4 available for combustion. On the other hand, the much smaller permeability of the SNL soil significantly reduces the effect of soil absorption of fuel from the surface pool. It is expected that subsurface infiltration effects in soils with lower permeabilities will not significantly reduce the available fuel for the surface fire. Simulations of infiltration into water-saturated soils also indicate minimal subsurface fuel infiltration due to a standing head of 20 cm of fuel on the surface for any of the soils considered. Unless a much larger head of surface fuel is attained in the spill, the spilled JP8 fuel will tend to float³ on the water-saturated soil. Infiltration rates of JP8 into variably saturated soils ($S_r < S < 1$) should fall somewhere in between those computed in this work for the two extreme cases of water saturation.

3. Fluids with a specific gravity greater than one will tend to sink, thereby displacing the *in-situ* water.

An approximate model for infiltration into dry soil, useful for inclusion as an algebraic boundary condition in a fluid dynamics model can be developed. However, a similar algebraic model for variably saturated soil would require significantly more effort. The model for dry soil would represent an upper bound on the amount of fuel absorbed by permeable, unsaturated soil in a fuel spill.

6.2 Heat-Driven Transport

Even though the verification studies indicate that there is a fair amount of uncertainty in the modeling of subsurface transport during a spill fire, the results do show that the fire is unlikely to continue to burn at the pool fire burn rate once the soil surface dries out (liquid fuel depleted by evaporation and drainage). The results for a 10 kW/m^2 heat flux indicate the combustion intensity dies off substantially when the surface dries out, because the wicking action is unable to supply fuel at a sufficient rate for more than 1-2 minutes following heat up of the liquid fuel to the boiling temperature. A 10 kW/m^2 heat flux is low for most pool fires (Gritz et al., 1996; Hamins et al. 1994), however the results suggest that a higher value of heat flux would only dry out the surface sooner and would therefore not alter the conclusion that the fire will not continue to burn vigorously beyond the dryout stage.

The so-called SNL soil, with a permeability of 0.07 darcy, results in mass fluxes that are too low to sustain the pool fire burn rate even before surface dryout. We conclude that lower permeability materials will not be able to sustain this level of surface fire either. The ingredients in a soil material necessary to allow a surface fire to burn at a similar rate prior to fuel pool depletion is high permeability and large wicking potential. In nature, these properties are typically inversely related. Large wicking potential is associated with a well-sorted material with a significant fraction of small pores, as can be ascertained from the Young-Laplace law for the capillary pressure as a function of pore size,

$$P_c = \frac{2\sigma}{r_{pore}}, \quad (11)$$

where σ denotes interfacial surface tension, and r_{pore} is an effective pore radius. On the other hand, permeability generally decreases as the characteristic pore size decreases. It seems unlikely that there exist many natural soils with high permeability (say 10 darcy or greater) which can generate capillary pressures much greater than those of the SNL soil. Otherwise, the materials considered in this study are not able to maintain a sufficiently vigorous fuel flux to the surface to maintain a burn rate similar to $0.063 \text{ kg/m}^2\text{-s}$ for any significant length of time.

The model results do raise another concern, that of a longer-duration low-intensity fire. This situation could be significant from a cook-off standpoint. The high-permeability alluvium indicates self-extinguishment just before 30 minutes into the simulation, or 15 minutes (accounting for a 5 minute time lag for preheating the fuel) after the surface pool of spilled fuel has been depleted. The Jornada soil, subject to a heat flux of 2 kW/m^2 begin-

ning at 41 minutes, produces mass fluxes greater than $0.002 \text{ kg/m}^2\text{-s}$ for up to about 100 minutes. Much lower values of fuel mass flux to the surface were found for the SNL soil. These results indicate that materials similar to the Jornada soil may be candidates for longer duration, low intensity fires which could pose a threat to weapon systems. What is needed to continue investigation of these scenarios is to establish the relationship between the surface fire intensity, the resulting heat flux to the soil surface and the associated mass flux of fuel from the subsurface to the surface fire. Follow-on work should be aimed at quantifying this relationship through experiments and modeling. At the same time, cook-off thresholds for ignition of high explosive can be used to estimate the danger posed by the low-intensity fires.

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APPENDIX A

Two-Phase Two-Component Thermal Model For Subsurface Transport

The governing equations for nonisothermal multiphase flow in porous media are statements of mass balance of water and air, over both liquid and gas phases, and a statement of energy balance, also over both phases (Peaceman, 1977; Martinez et al, 1997). The canonical form of this coupled system of balance equations is given by

$$\frac{\partial}{\partial t} \begin{bmatrix} d_w \\ d_a \\ e \end{bmatrix} + \nabla \bullet \begin{bmatrix} F_w \\ F_a \\ q \end{bmatrix} = \begin{bmatrix} Q_w \\ Q_a \\ Q_e \end{bmatrix}, \quad (12)$$

where subscripts w and a denote water and air, respectively, and e corresponds to energy. The bulk mass and energy densities are given, respectively, by,

$$\begin{aligned} d_\alpha &= \phi \sum_{\beta=l,g} Y_{\alpha\beta} \rho_\beta S_\beta, & \alpha &= w, a \\ e &= (1 - \phi) \rho_s e_s + \phi (S_l \rho_l e_l + S_g \rho_g e_g) \end{aligned} \quad (13)$$

In these and subsequent equations subscripts l , g , and s refer to the liquid, gaseous, and solid phases, respectively. Also, ϕ denotes porosity, $Y_{\alpha\beta}$ is the mass fraction of component α in phase β , ρ is phase density, e is internal energy, and S_β is phase saturation, and the pore space is assumed fully occupied by the liquid and gas phases, $S_l + S_g = 1$. The net component mass fluxes are defined as

$$F_\alpha = Y_{\alpha l} \rho_l v_l + Y_{\alpha g} \rho_g v_g - \rho_g D_{\alpha g} \nabla Y_{\alpha g}, \quad (14)$$

where v_β denotes the Darcy flux vector and $D_{\alpha g}$ is a pressure- and temperature-dependent effective binary diffusion coefficient. The advective fluxes are described by the extended Darcy law, in which relative permeabilities are introduced to account for the multiphase motion of fluids. Thus the Darcy flux vector of phase β (liquid or gas) is,

$$v_\beta = -\frac{k_{r\beta}}{\mu_\beta} k \bullet (\nabla P_\beta + \rho_\beta g) \quad (15)$$

where P is pressure, g is the gravitational acceleration vector, and μ is dynamic viscosity. The intrinsic permeability tensor of the medium is k and the relative permeabilities are denoted $k_{r\beta}$. The intrinsic permeability tensor is assumed to be a property of the material under consideration, and as such is a spatially heterogeneous quantity. Note that we have assumed that each phase has its own phase pressure. The phase pressures are related via the capillary pressure relation, $P_g - P_l = P_c(S_l)$, which, as indicated, is assumed to be em-

pirically specified as a function of the phase saturation of liquid. The net heat flux vector is defined by

$$\mathbf{q} = -\lambda_T \nabla T + \sum_{\beta} \rho_{\beta} \mathbf{v}_{\beta} h_{\beta} + \sum_{\alpha} h_{\alpha g} \mathbf{J}_{\alpha g} \quad (16)$$

where λ_T is a saturation-dependent effective conductivity, h_{β} is phase enthalpy, $h_{\alpha g}$ is the enthalpy of component α in the gas phase, and $\mathbf{J}_{\alpha g}$ is the gas-phase diffusion flux, the last term on the right-hand-side of Eq. (14).

The foregoing describes the major components of the mathematical model. Some additional information concerning thermodynamics and transport models can be found in (Martinez et al., 1977).

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