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BURNING OF LIQUID POOLS
IN REDUCED GRAVITY

by

A. Murty Kanury

Final Report

of

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16. Abstract

The existing literature on the Combustion of liquid fuel pools is reviewed to identify the physical and chemical aspects which require an improved understanding. Among the pre-, trans- and post-ignition processes, a delineation is made of those which seem to uniquely benefit from studies in the essential environment offered by Spacelab. High-lighting the role played by the gravitational constant, analytical and experimental justifications are developed for a Spacelab study of about a dozen different phenomena. The analytical justifications are based on hypotheses, models and dimensional analyses whereas the experimental justifications are based on an examination of the range of gravity and gravity-dependent variables possible in the earth-based laboratories. Some preliminary expositions into the questions of feasibility of the proposed Spacelab experiment are also reported. To resolve some of these feasibility issues and to develop the experiment design for installation in the Spacelab are the immediate future steps.

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CONTENTS

A. PRELUDE

Rationale, Approach and Methods of Attack: The objective of our research is to examine the existing literature on pool burning to find if there exist any experiments that would benefit science and society by their conduct in the Spacelab. This examination involves a thorough literature review, an identification of those aspects of pool burning in which there exists a need to improve our understanding, a delineation of such aspects as may benefit from the essential environment offered by Space Shuttle, a theoretical and experimental justification of studies in space and a feasibility/development program.

In order to chart out a systematic road map for this study and to rigorously follow the course of progress in the program we have developed the chart shown in Table I enumerating the appropriate decision-making questions in their order. This chart is useful not only in our pool burning project but also in any other project of relevance to the space program.

Note that in our pool burning project, the first thirteen items of the chart are concerned with analytical and experimental justification and impact of the experimental data from space. Items 14 and 15 of the chart address feasibility analyses. Item 16 stands for preliminary experiment design. Items 17-20 do not presently come into our first year project but it is well to keep in mind the overall perspective of where we are going as we proceed through the current project.

TABLE I

PACE LOGIC CHART

1. Given a topic
2. Examine its importance societally and scientifically
3. By reviewing the existing knowledge.
4. Do crucial gaps exist in the present knowledge?
5. If no, abort.
   If yes, are these gaps removable by research?
6. If no, abort.
   If yes, then there is a NEED for research.
7. Can this research be done on earth?
8. If yes, substantiate and abort.
   If no, continue.
9. Is the essential environment of space lab beneficial?
   If no, abort.
   If yes, show in detail how and why.
10. Then, enumerate the ADVANTAGES of doing this work in space.
11. Can the ideas stimulated by the possibility of space experiments be somehow simulated on earth-say for example by gravity and pressure modeling?
12. If yes, can these simulations cover a wide enough range of the variables?
    If yes, substantiate and abort.
    If no, substantiate and proceed.
13. Then the space experiments are UNIQUE.
    By now we have identified the needed experiments which are advantageous to be conducted in space and are uniquely conductible in space.
14. Are the necessary, advantageous, unique space experiments POSSIBLE to be carried out in space?
    If no, examine why and abort.
    If yes, proceed.
15. Conduct feasibility studies, modify methods of implimentation constantly remembering the goals of the experiment. Check the theoretical concepts of the experiment. Implications and impacts of the results.
16. Develop Paper-and-pencil design of the experiment(s) with due consideration of the safety in execution.
17. Develop the experimental hardware.
18. Conduct laboratory experiment to debug the apparatus.
19. Conduct droptower and aircraft tests with the apparatus to check the soundness of the hypotheses even if the data are limited, and to obtain refinements in apparatus.
20. Integrate the experiment(s) with other combustion experiments evolving from the PACE program to develop portable modules for the shuttle flight.

B. INTRODUCTION

General: The overall objective of our research is to

a. Examine the existing analytical and experimental work on the burning of liquid pools in order to identify and assess the scientific and societal basis for conducting research in space.

b. Based on this justification, then, develop recommendations for further feasibility studies that will lead to space experiments.

The research is essentially a paper study. The feasibility studies will perhaps lead into some laboratory work.

Problem Break-Down: The pool burning problem area has several phases, processes and phenomena. For example, we have to consider the details of

a. Formulation of pools. Liquid disposition and movement. Evaporation without combustion.

b. Following this evaporation we have to follow the transient dispersion of the fuel vapor in the gas-phase to locate the combustible domain and its movement with time.

c. Given the temporally propagating combustible domain, what are the ignition characteristics? Both the formation of the combustible domain and its ignition depend upon the initial temperature of the liquid relative to the fuel's flash point.

d. Once ignited, how would the flame spread? How are the gas- and liquid-phase processes interconnected by the moving source flame? What are the mechanisms of energy and species transport?

e. If the flame spread occurs to cover the entire pool, are there any identifiable steady state burning characteristics of the pool? Burning rate, flame shape, size and color, thermal radiation etc., are but a few of the apparently important variables.

f. What is involved in the extinction and extinguishment of the pool fire? How does chemistry of combustion come into play in these processes?

Comments: a. Each of these aspects of pool fire has some important unanswered questions. Several of these aspects also share some features in common. In general, dispersion of heat and species as influenced by gravitational effects acts both as cause (ex: species distribution and residence time to alter radiation and to contribute to preferential diffusion) and effect (ex: the already slow physical processes will become even slower under reduced gravity thus making the flames closer to ideal diffusion flames). The crucial question then arises - do the ideal diffusion flames which are demonstrated to be of theoretical convenience really exist? If the physical processes are progressively slowed down relative to chemical processes, thus approaching the ideal limit of Damkohler number of zero to realize ideal diffusion flames, does not some phenomenon akin to flash-back come to tamper with our convenience?

b. There are some immediate experiments that come to mind with intriguing practical and theoretical possibilities. These experiments are relevant to one or more of the aspects of pool fire discussed in section C. Four of these experiments are:

1. Flash Point Experiment in which a Droplet Moves Through a Heated Tube:

This experiment will remove any ambiguities imposed by solid boundaries on the measured flash point. The solid boundaries influence the heat and mass augmentation rendering extrinsic variance to the measurements in the classical open (or closed) cup flash point testers.

2. Experiment to Demonstrate Mixing as an Essential Part of Combustion:

By mixing, we mean here, the gas-phase mixing of fuel vapors with the ambient oxygen. Both molecular diffusion and turbulent turmoil are expected to contribute to the mixing, the latter being strongly influenced by gravity and inertia of the flow.

3. Surface Tension Driven Flows:

That convection induced by the temperature-dependent surface tension of the liquid fuel contributes heavily to the feed-forward of energy in flames propagating over contiguous surfaces is a well known fact. Not withstanding this familiarity, the precise balance of surface tension forces with gravitational and inertial forces is less than clearly understood. A scrutiny of the detailed flow patterns in the liquid-phase under carefully controlled, measurably imposed, forces should dispel the existing ambiguities regarding the role played by Marangoni surface-tension effects.

It seems that in this concern we are also seeking to understand the condensed-phase mixing phenomena and their consequences. Mixing if violent enough might serve just the opposite of what is expected when mixing is gentle and mild. For example, while the surface-tension driven flow may increase flame propagation rate over a liquid fuel surface due to the fact of the enhanced feed-forward heat transfer rate, excessive mixing may lead to vanishing temperature gradients in the liquid and preclude attainment of surface temperatures high enough to result in substantial fuel vapor partial pressures. In this discussion we used such words as "violent enough" and "high enough". What is the threshold level of mixing beyond which the effects are unexpected or unfavorable to start and sustain a flame?

C. PHYSICS OF POOL BURNING

CHAPTER C I

CONDENSED-PHASE PROCESSES IN PREIGNITION EVAPORATION
[Case 1: Surface Tension Flows Unsuppressed.]

The Problem:

Consider a 'quiet' pool of a liquid situated in a quiescent atmosphere. The liquid's interior and surface temperatures are respectively T_R and T_W. Let the temperature of the atmosphere be T_∞. Normally T_∞ will be larger than T_W which is larger than T_R. Heat is transferred from the atmosphere to the liquid and extended partly to provide for the latent heat of evaporation at the surface and the rest to raise the sensible enthalpy of the liquid. If a steady state is attained, the sensible enthalpy rise will be commensurate with the evaporative regression rate. If the ambient atmosphere is cooler than the liquid's interior, however, the reservoir loses heat to and through the evaporating surface to the ambience. Because of the particular magnitude and combination of thermal properties of the liquid and gas-phases, the heat lost to the atmosphere may usually be neglected. All the heat lost by the liquid reservoir may then be approximated to have been expended for surface evaporation.

In situations complying with this description, the evaporating surface is cooler and hence denser than the interior of the liquid. The unstable density distribution culminates in a flow pattern which tends to mix the liquid-phase.

This problem has a range of important practical applications. On a large scale the unstable flow and mixing are relevant in prediction and management of aquatic life and pollutant sedimentation in lakes and rivers. The same considerations will help in prediction of freezing of lakes and rivers as well. On a moderate scale, design of many multiphase contact devices of chemical process industry (i.e., distillation, absorption, separation and extraction units) calls for a prediction of the flow velocities, and heat and mass transfer.

The problem also poses an intrinsic scientific challenge of invoking an interaction of several natural forces.

Past Work:

Over a hundred years ago, James Thompson, a Civil Engineering lecturer in Belfast and the older brother of Lord Kelvin, published a note on certain curious motions observable at the surfaces of wine and other alcoholic beverages [1]. He attributed these evaporative convective motions to variations in the liquid's surface tension. Later on Thompson also observed motions in a tub of soapy water [2] which he attributed to bouyancy forces stemming from evaporative cooling.

Both surface tension and buoyancy mechanisms result from the evaporative cooling of the liquid surface causing an increase in both the density and surface tension. An unstable stratification arises inducing the observed flow. Two other known ways of producing similar unstable flows are: First, by heating a fluid layer at the bottom and cooling at the top; and, second, by discretely separating binary solutions of liquids of different densities and surface tensions.

In an excellent exploratory study Berg, Boudart and Acrivos [3] recently presented a series of systematic schlieren visualizations of flows stemming from evaporative cooling. With tests on eight different fluids, these authors demonstrate that the fluid layer depth (if less than 1 cm) and surface contamination are two of the most dominant factors influencing the observed flow patterns. The evaporation rates of the various liquids are measured in a 10 cm x 10 cm tank of depth 1.25 cm, this depth being chosen on the basis of the observation that the liquid depth of more than about 1 cm did not materially alter the observed flow patterns. No attempt has been made to postulate a quantitative hypothesis to correlate the data.

Our Hypothesis:

A tentative hypothesis may be forwarded here to explain the observations.

It is reasonable to expect that the flow patterns as well as the heat and mass transfer are dependent upon a balance among forces of surface tension, viscosity and buoyancy. Among the variables that influence the flow and evaporation rate $\dot{m}''$ are: the gravitational constant g; the temperature T (or density ρ) differences between the liquid's interior (subscript R) and the evaporating surface (subscript W); fluid layer thickness δ; and the fluid properties of surface tension σ, dynamic viscosity μ, thermal expansion coefficient β, conductivity K, density ρ, and specific heat C_p.

Fixing x and y coordinates laterally and normally respectively in the fluid layer, with d representing the pool diameter and v representing the y-directional velocity, the following order-of-magnitude analyses can be carried out.

For mass conservation,

$$v \simeq \dot{m}''/\rho_W \tag{1}$$

Equating the viscous force due to the vertical flow and the surface tension force,

$$\mu \frac{\partial v}{\partial x} \cdot \pi d \delta \simeq \frac{\partial \sigma}{\partial x} \cdot \frac{\pi d^2}{4}$$

Thus

$$\dot{m}'' \simeq \frac{\sigma \rho_W}{\mu} \quad \frac{d}{4\delta} \tag{2}$$

Similarly, a balance between viscous and buoyancy forces is given by

$$\mu \frac{\partial v}{\partial x} \cdot \pi d \delta \simeq g(\rho_W - \rho_R) \cdot \frac{\pi d^2}{4} \delta$$

so that

$$\dot{m}'' \simeq (\frac{d}{4\delta})^2 \cdot 4 \cdot \frac{g\delta^2}{\mu} \quad \rho_W (\rho_W - \rho_R) \tag{3}$$

Finally, balancing convective and conductive heat flow rates,

$$v \frac{\partial T}{\partial y} \cdot \frac{\pi d^2}{4} \approx \frac{K}{\rho_W C_p} \cdot \frac{\partial^2 T}{\partial y^2} \cdot \pi d \delta$$

so that

$$\dot{m}'' \approx \frac{K}{C_p \delta} \cdot \frac{4\delta}{d} \tag{4}$$

Equations (2)-(4) reveal that the problem may be fully described by six non-dimensional parameters.

$$\left[\frac{\dot{m}''\delta}{\mu}\right] = f\left\{\left[\frac{4\delta}{d}\right], \left[\frac{K}{C_p \mu}\right], \left[\frac{\delta\sigma\rho_W C_p}{\mu}\right], \left[\frac{g\delta^3\rho_W^2}{\mu^2}\right], \left[\frac{\rho_W - \rho_R}{\rho_W}\right]\right\} \tag{5}$$

$(\dot{m}''\delta/\mu)$ is one sort of mass transfer Nusselt number. (δ/d) is a geometric parameter indicative of the shallowness of the pool. $(K/C_p\mu)$ is Prandtl number. $(\delta\sigma\rho_W C_p/\mu K)$ is a primitive form of Marangoni-Thompson number. The product of the final two bracketed nondimensional parameters is the well-known Grashof number.

If (δ/d) is kept invariant or if the pool depth is irrelevant, this parameter could be removed from consideration. The Prandtl number could be considered more or less invariant with the liquid so far as liquid metals are not included in the study. Or alternatively, the Prandtl number can be combined with the dependent parameter of nondimensional evaporation rate. If δ is of no consequence (as learned from preliminary observations), the Grashof and Marangoni numbers could be so combined as to eliminate δ. Thus the simpler special form of Eq. (5) becomes

$$M^* \equiv \left[\frac{\dot{m}''\delta C_p}{K} \cdot \frac{K}{C_p \mu}\right] = f\left[\frac{g\mu K^3}{\rho_W \sigma^3 C_p^{\,3}} \cdot \frac{\rho_W - \rho_R}{\rho_W}\right] \equiv f(G^*) \tag{6}$$

Discussion and Conclusion:

An attempt to correlate Berg's brief measurements by Eq. (6) is shown in Table II and Figure 1. This attempt is an indication of neither the quality of Berg's data nor the fallibility of the present hypothesis. It is, however, absolutely clear that this practically important and scientifically intriguing problem requires further study both experimentally and theoretically. The use of variable gravity g to achieve an otherwise unobtainable broader range of variation in G^* is imminently clear from Eq. (6).

TABLE II

Material	σ dynes/cm	ρ gm/cm^3	μ gm/cm sec	β $^oK^{-1}$	K cal/cm sec^{o}C	$\dot{m}''$ gm/cm^2 sec	C_p ca;/gm^{o}K	G^*	M^*
	EVAPORATION RATES MEASURED BY BERG et al. [3]						MANIPULATIONS PER THE PRESENT HYPOTHESIS		
Acetone	23.7	0.729	3.26×10^{-3}	1.487×10^{-3}	4.543×10^{-4}	5.6×10^{-7}	0.506	35.52×10^{-17}	0.78×10^{-3}
Benzene	28.8	0.879	6.52 "	1.237 "	3.780 "	3.2 "	0.411	29.27 "	0.435 "
CCl_4	26.9	1.463	9.69 "	1.236 "	2.470 "	2.8 "	0.500†	4.98 "	0.710 "
Dioxane	33.5	1.035	13.51 "			1.7 "			
Heptane	20.3	0.684	4.09 "	1.240 "	3.354 "	1.7 "	0.525	22.69 "	0.330 "
i-propanol	21.4	0.785	26.00 "	1.410 "	3.362 "	2.3 "	0.500†	141.69 "	0.428 "
Methanol	22.6	0.793	5.97 "	1.199 "	4.812 "	3.7 "	0.566	47.12 "	0.544 "
Water	73.0	0.998	10.05 "	0.207 "	14.290 "	1.5 "	1.000	1.53 "	0.131 "

† estimated.

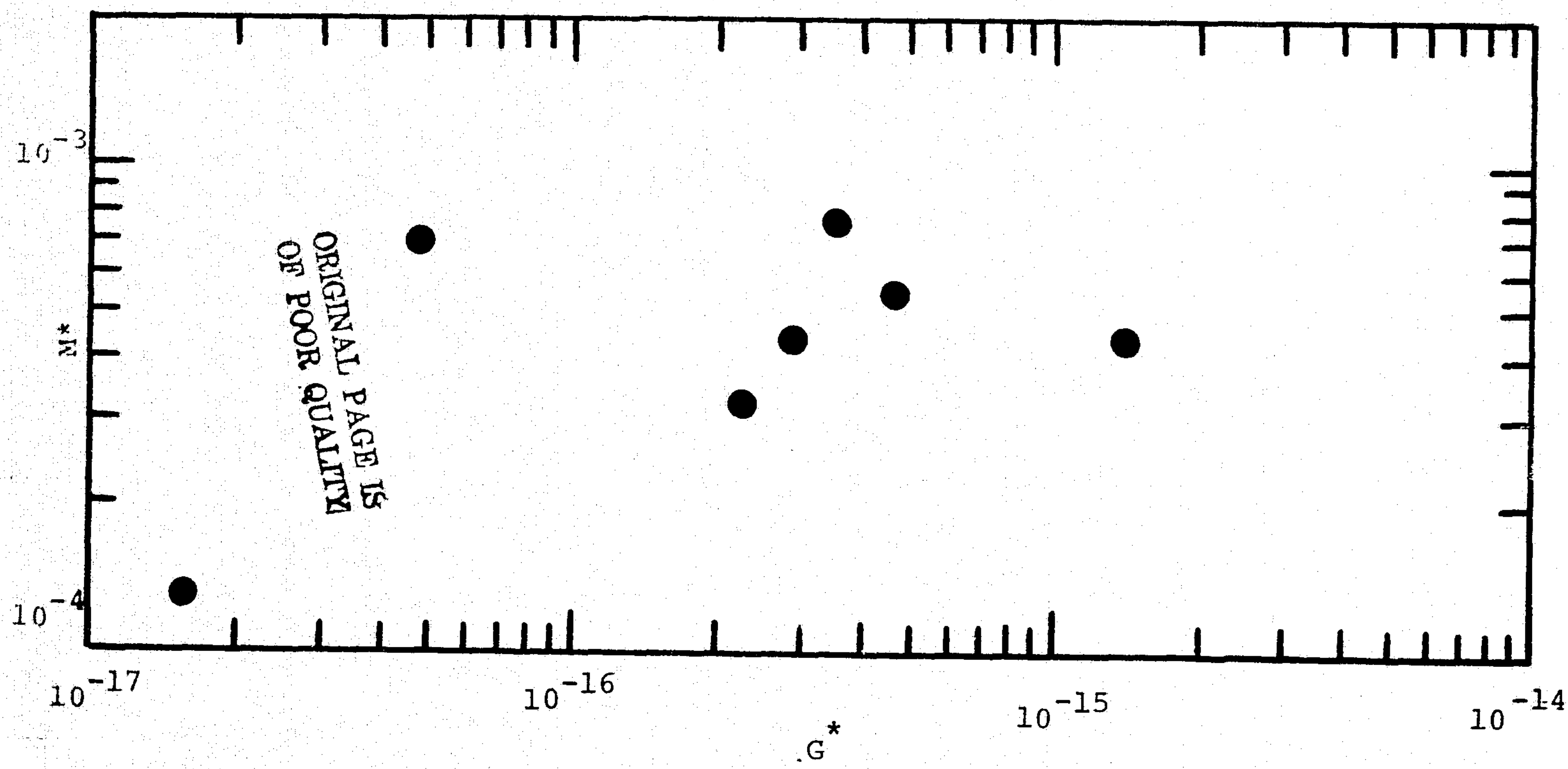

Figure 1
Correlation of Berg's Data with Our Hypothesis

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CONDENSED-PHASE PROCESSES IN PREIGNITION EVAPORATION
[Case 2: Surface-Tension Flows Suppressed.]

Statics:

Consider a pool of liquid whose hydrodynamic structure is determined by a balance between viscous, gravitational and surface-tension forces. A case in which all of these three forces come into play is discussed in Chapter CI. When, by scheme or by chance, one of these forces is immensely reduced in magnitude, say reduced are the gravitational body forces, other forces become more defined and influential. In this chapter we examine the conditions under which surface-tension and gravity forces are important to arrive at some simple estimates of the structure of the liquid-phase. Specifically, we seek to learn about the composure and mixing of the liquid pool, such learning being required in the design of the liquid pool for Spacelab experiments.

Suppose that the liquid is held in a tube of diameter d standing in a pool. Let the ambient pressure be P_∞. Let η be the height to which the capillary column in the tube rises. (Obviously a meniscus is formed due to the wetting characteristics of the tube-walls and the liquid. η is measured from the base of the capillary column, i.e., from the pool surface to the apex of the meniscus.) The pressure distribution along the height of the capillary column is then given by $dP/dy = \rho g$ so that $\Delta P = \rho g \eta$ where ΔP is the pressure head due to the column. A force balance on the completely wetting meniscus gives ΔP in terms of the surface-tension σ. $\Delta P \pi d^2/4 = \sigma \pi d$ so that $\Delta P = 4\sigma/d$. Equating these two relations, the balance between gravity and surface tension determines the height of the column according to

$$\frac{\eta}{d} = 4 \quad \frac{\sigma}{\rho g d^2} = \frac{4}{Bo} \tag{7}$$

where Bo is Bond number defined as $\rho g d^2/\sigma$ [4]. This nondimensional parameter compares the magnitude of gravitational body forces to capillary surface forces. When Bo is much greater than unity, gravity forces overwhelm the negligible surface tension effects. This limiting case arises not only when the gravitational constant g is larger but also when the fluid density and tube (or pool) diameter are large. When Bo is much smaller than unity, i.e., when a liquid of low density and high surface tension is held in a capillary tube at reduced gravity, gravitational effects are unimportant.

Note that for scaling to preserve the liquid surface structure invariant under various gravity conditions, the pool diameter d has to be chosen proportional to $g^{-1/2}$ so that gd^2 remains invariant and hence, for a given liquid (σ,ρ), the Bond number remains invariant.

The scaling technique is interesting in a different view point as well. Suppose g is kept fixed at the earth value. A gradual reduction in d then brings about a gradual reduction in the Bond number to ultimately result, in the limit $d \to o$, $Bo \to o$, a surface which is characteristic of zero gravity condition. Being controlled by surface-tension effects but not by gravity effects, this situation behaves independently of the orientation of the surface with respect to the gravity vector. Man has used this situation for a long time both in practical applications (e.g.: use of wicks to support and transfer liquids) and in scientific work (e.g.: use of sand-filled pans or ceramic wicks to support various liquid fuels in any specified geometry and orientation for study of combustion and flames [5]). Conceptually, a liquid pool in a sand-filled pan is composed of a very large number of tiny pools, namely the pores of the wick. The effective Bond number for this situation is near zero so that the fuel-soaked wick could be held in any orientation without losing the liquid for whatever study is required.

Dynamics:

If the fluid under consideration is in motion with a velocity v, inertia forces come into picture. Weber number $We \equiv \rho v^2 d/\sigma$ is the ratio of inertia to surface-tension forces. Froude number $Fr \equiv \rho v^2/\rho g d$ is the ratio of inertia to gravity forces. Note that $We/Fr = Bo$.

According to the scaling law mentioned earlier to preserve Bond number, the scale of the experiment has to be proportional to the inverse square root of the gravitational constant, $d \propto g^{-1/2}$. For this scaling law to continue to hold even in the additional presence of inertial forces introduced by externally controlled velocities v, one has to preserve the Weber number invariant. This is done by adjusting the velocity v to be proportional to $g^{1/4}$. Thus v is also proportional to $d^{-1/2}$ and the Froude number invariance is automatically fulfilled.

In some instances viscous forces may also enter into the picture. The ratio of inertial forces to viscous forces is known as Reynolds number $Re = \rho v d/\mu$. The following matrix demonstrates the forces and the dimensionless numbers of concern. The four forces - viz: inertia, gravity, capillarity and viscosity - are listed both in the column and row first. Ratios of various terms are then made to complete the matrix with the numbers.

	ρv^2	$\rho g d$	σ/d	$\mu v/d$
ρv^2	1	Fr	We	Re
$\rho g d$	Fr^{-1}	1	Bo	π^*
σ/d	We^{-1}	Bo^{-1}	1	Ca
$\mu v/d$	Re^{-1}	π^{*-1}	Ca^{-1}	1

where the following definitions hold.

Froude No. $Fr = \rho v^2/\rho g d$, Weber No. $We = \rho v^2 d/\sigma$

Bond No. $Bo = \rho g d^2/\sigma$, Reynolds No. $Re = \rho v d/\mu$

No-name No. $\pi^* = \rho g d^2/\mu v$, Capillary No. $Ca = \sigma/\mu v$

In order to see which force among capillary, inertia and gravity forces is the most important in a given situation, we have developed Figure 2 in which the three dimensions represent the three nondimensional ratios We, Fr and Bo. Where these three axes intersect - i.e., in the midpoint of the large box We = Fr = Bo = 1. Quadrants in which these numbers are less than or greater than unity are then drawn to identify the eight (small boxes) domains marked 1,2 ... 8.

In box 1, for example, We$<$ 1, Fr$<$ 1 and Bo$<$ 1; therefore inertial forces are less than buoyancy forces which are less than the capillary forces; and thus we identify box 1 to be domain of capillary force domination. Similar scrutiny gives that box 4 is also a capillary-controlled domain. In boxes 2 and 7, buoyancy dominates; and in boxes 5 and 8, inertia dominates. The scheme does not lead to any conclusive statements regarding boxes 3 and 6, this ambiguity modifying Figure 2a to the form of Figure 2b.

The issue of whether or not viscous effects are important is a separate one and has to be settled separately by consideration of the nondimensional numbers of the last column in our matrix, namely Re, π^* and Ca.

The response times (or relaxation time) associated with each of the force-control may be easily estimated by the following simple relations.

Controlling Force	Response Time
Inertial	(d/v)
Buoyant	$(d/g)^{-1/2}$
Capillary	$(\rho d^3/\sigma)^{1/2}$
Viscous	$(\rho d^2/\mu)$

Comments

One of the main reasons for studying the liquid-phase statics and dynamics is to determine the heat transfer in the liquid-phase and the consequent fuel vapor production. At sufficiently low values of g, free convective transport

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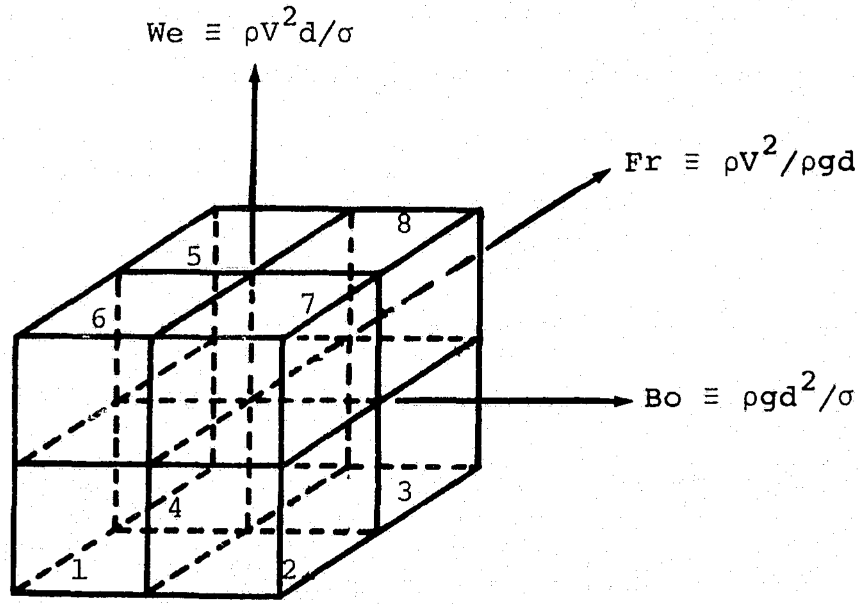

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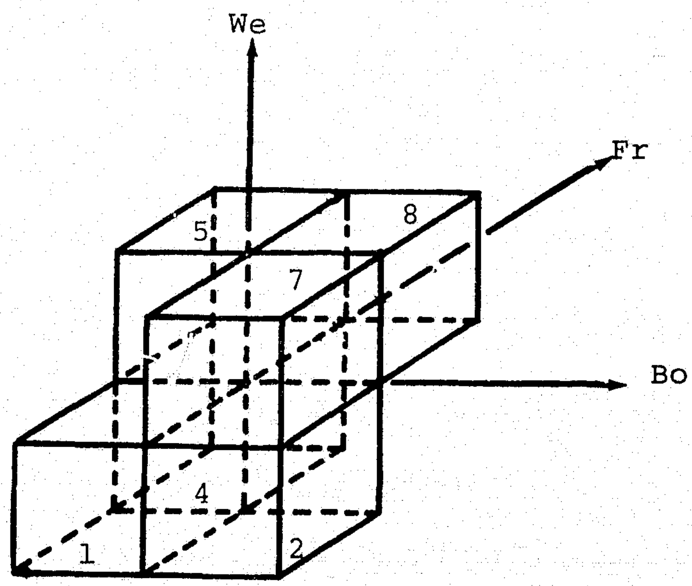

b

Figure 2

Regimes of Control with Fixed Viscous Forces mechanisms are suppressed and the diffusive mechanisms are accentuated in their importance. The explicit problem of heat transfer in condensed-phase will be discussed elsewhere in this project.

Manipulation of the relative role played by buoyancy forces may be done by varying the appropriate variables: the volume or linear dimension, the density, density differences, and the gravitational constant. The range of variation achievable in a relevant nondimensional group by varying one or more of these participant variables is a matter of economics, complexity and convenience. But it is well to remember that with the availability of the opportunity to use the Space Shuttle, one has the capability to realize long steady durations of reduced or programmed gravity conditions thus widening the range of phenomena that could be covered.

CHAPTER C III

HEAT TRANSFER IN THE CONDENSED PHASE

Consider a pool of diameter d and depth δ containing a liquid of density ρ, specific heat C_p, conductivity K, radiation absorption coefficient k, heat of vaporization Δh_{vap}, viscosity μ, molecular weight M, vapor pressure constant P_v and surface tension with air σ. Let the initial temperature of this liquid be T_o. Let the ambient temperature be T_∞, perhaps only slightly different from T_o. Let the ambient air be in such a motion as to result in a heat transfer coefficient h between the air and the liquid surface.

Now, impose for time $t \geq 0$ a thermal radiation flux I_o on the liquid surface. Measuring y from the liquid surface, into the liquid, normal to the surface and x along the liquid surface, our problem is to find the transient temperature distribution in the liquid x,y space. Let v and u be the velocity components in y and x directions respectively. The energy equation for the problem takes the following form after neglecting those gradient terms which are insignificant. Here $\dot{m}''$ is the evaporative mass transfer rate.

$$\rho C_p \frac{\partial T}{\partial t} - \dot{m}'' C_p \frac{\partial T}{\partial y} = K \frac{\partial^2 T}{\partial y^2} + 2 I_o\, k\, E_2(ky) \qquad (8)$$

The origin $y = 0$ is fixed on the regressing surface of velocity. $v = \dot{m}''/\rho$. E_2 is the second degree exponential integral, E_n being defined by

$$E_n(\gamma) \equiv \int_1^\infty e^{-\gamma\phi} \phi^{-n} d\phi \equiv \int_o^1 \phi^{n-2} e^{-\gamma/\phi}\, d\phi$$

The second term on the right hand side of the energy equation accounts for absorption of radiation in the liquid. If the external radiant energy source were coherent (say, from a tuned laser beam), then $E_2(ky)$ is replaced by Beer-Bouguer factor $\exp(-ky)$, with a change of the beam length factor 2 to 1.

The y-momentum equation takes the form

$$\rho\frac{\partial v}{\partial t} - \rho v \frac{\partial v}{\partial y} = \frac{\partial P}{\partial y} - \mu\frac{\partial^2 v}{\partial x^2} \tag{9}$$

The x-momentum conservation is assumed, for now, to be given by vanishingly small u and its gradients. $\partial P/\partial y$ in Eq. (9) is usually small except under certain special circumstances related to the magnitude of the absorption coefficient k; this matter is discussed later on in this chapter. The boundary conditions for Eqs. (8) and (9) are as follows, assuming that δ, the depth, is sufficiently large. Initially, for all values of y, the temperature is uniformly initial, and the velocities are nil; $T(y,o) = T_o$ and $v(y,o) = 0$. As one examines the indepth, liquid temperature will be initial T_o and the velocity will be zero; the gradients will also be vanishing; thus, $T(\delta,t) = T_o$, $v(\delta,t) = 0$, $\partial T/\partial y|_{\delta,t}=0$, $\partial v/\partial y|_{\delta,t} = 0$. At the surface, the temperature gradient is related to convective heat loss to the environment and to the evaporative heat sink, the velocity is related to vaporization rates thus, $-K\partial T/\partial y|_{0,t} = h(T_\infty - T(o,t)) - \Delta h_{vap}\dot{m}''$ and $v = \dot{m}''/\rho$.

We further note that the mass transfer rate $\dot{m}''$ is given, by Dalton's law of diffusion in gas-phase, as

$$\dot{m}'' = h_D(Y_{FW} - Y_{F\infty}) \tag{10}$$

where Y_F is the fuel mass fraction, W is for the vaporizing surface and ∞ is for ambience. h_D is mass transfer coefficient determined by the ambient air flow in the same manner as the heat transfer coefficient h. If the Lewis number $Le \equiv \alpha_g/D_g$ of the air + fuel vapor mixture is unity, $h/C_g = h_D$. (Here, α, D and C are respectively the thermal diffusivity, mass diffusivity and specific heat with the subscript g referring to gas phase.) We further may relate the fuel fraction at the surface to the saturation equilibrium partial pressure P_{FW}

at the surface temperature.

$$Y_{FW} = \left\{ 1 + \frac{M_g}{M_F} \left(\frac{P_g}{P_v} \exp\left[-\Delta h_{vap}/RT_W \right] - 1 \right) \right\}^{-1} \qquad (11)$$

Where M_g is the molecular weight of the gas phase mixture, M_F is that of fuel vapor, P_g is the total ambient pressure, P_v is the characteristic vapor pressure constant of the liquid, R is the gas constant of the vapor and T_W is the temperature at $y = 0$, time-dependent according to the solution of Eq. (8).

When k is small, significant fraction of the thermal radiation is absorbed in depth. This indepth absorption may shift the highest temperature location from the surface $y = 0$ to some depth y which is finite, positive. Under these circumstances, the heating process is unstable and significant flow patterns are possible. The term $\partial P/\partial y$ is Eq. (9) then becomes nonnegligible and equal to $g(\rho-\rho_o)$ where g is acceleration due to gravity. The flow would also introduce a nonuniformity in the evaporating surface temperature, the most dominant consequence of this nonuniformity being introduction of surface-tension-related driving force/resistance to the flow via the boundary condition for Eq. (9); $-\mu\partial v/\partial x|_{o,t} = \partial\sigma|\partial x|_{o,t}$.

Defining

$$\theta \equiv (T-T_o)/T_o \quad ; \quad V \equiv \rho v/h_D$$

$$\tau \equiv Ktk^2/\rho C_p; \quad \eta \equiv ky; \quad \xi \equiv x/d$$

the solution of the problem $\theta = \theta(\eta,\xi,\tau)$ and $V = V(\eta,\xi,\tau)$ involves the following dimensionless parameters.

$$\beta \equiv I_o/KkT_o; \quad \Delta \equiv k\delta; \quad a \equiv \delta/d; \quad Pr \equiv K/\mu C_p$$

$$M^* \equiv M_g/M_F; \quad P^* \equiv P_g/P_v; \quad \mathcal{C}_p \equiv C_p/R$$

$$\mathcal{H} \equiv \Delta h_{vap}/C_p T_o; \quad \mathcal{B} \equiv \Delta\rho/\rho; \quad Bo \equiv gd^2 \rho/\sigma$$

$$Nu^* \equiv h_D C_p d/K; \quad Gr \equiv gd^3 \frac{\Delta\rho}{\rho} \frac{\rho^2}{\mu 2}$$

The dominant gravitational effects come via the Bond number governing the surface tension effects and the Grashof number governing the concensed phase as well as gas phase mixing and dispersion..

If the velocity u were not neglected as done above, but were related to v via the continuity equation $u/\delta \simeq v/d$, and then substituted into $\rho C_p u\delta/K$, the ratio of surface-tension-related convective heat flux to normal conductive heat flux,then the so-called Marangoni-Thompson-(Peclet) number arises in place of the Bond number above.

CHAPTER C IV

POOL EVAPORATION

Consider a long parallel plate duct placed horizontally. (The significance of this duct in pool study will be discussed later.) Let this duct be partially filled with a liquid at temperature T_R. Let the upper portion of the duct, left unfilled by the liquid, consist of a gentle transverse air (or any other ambient gas) flow at a temperature T_∞. Both the liquid temperature and ambient temperature may be higher or lower than the saturation temperature of the liquid corresponding to the prescribed ambient pressure. Heat may flow to or from (and through) the liquid air interface in any normal direction. Evaporation then takes place increasing the local vapor mass fraction in the air stream. To find (a) the rate of evaporation, (b) change in ambient temperature and vapor content, and (c) change in the liquid temperature constitutes the problem on hand.

Conservation of fuel vapor mass is given by a balance between the evaporation rate and the increase in the fuel concentration in the ambient stream.

$$-d\dot{m}_F = \dot{m}_\infty dY_{F\infty} \tag{12}$$

Here $\dot{m}_F$ is the fuel (F) evaporation rate (gm /sec) the minus sign indicating that it is evaporative mass loss rather than condensative mass gain by the reservoir. $\dot{m}_\infty$ is the air flow rate (gm /sec) and $Y_{F\infty}$ is the fuel vapor (F) mass fraction in the ambience. The differential signs are meant to mean that the quantities refer to a small differential interface area. By Dalton's law of evaporation [6], $-d\dot{m}_F = h_D\ (Y_{FW}-Y_{F\infty})dA_W$ where the subscript W refers to the evaporating surface, the quantity h_D is the local mass transfer coefficient (gm/cm^{2}sec) and A is area. With this relation, Eq. (12) becomes

$$\dot{m}_\infty dY_{F\infty}=h_D(Y_{F\infty}-Y_{FW})dA_W \tag{13}$$

If the air stream is not heated or cooled by extraneous means at the dry (i.e., upper) wall of the channel , its enthalpy change is solely due to the heat exchange with the liquid surface. Now, visualizing a control boundary on the air side immediately over the liquid surface, the enthalpy balance across a small liquid surface area dA_W is given by

$$\dot{m}_\infty\ di_\infty= h_g(T_W-T_\infty)dA_W+i_f\dot{m}_\infty dY_{F\infty} \tag{14}$$

The left hand side quantity is the increase in the enthalpy (i) of the air stream. The first term on the right hand side is the convective heat transfer (with heat transfer coefficient h_g) and the last term is the evaporative heat sink (with $i_f\equiv$ total heat of vaporization).

The control volume may also be placed immediately under the liquid surface. Then the heat loss across the liquid surface to the ambience, $\dot{m}_\infty di_\infty$, is equal to the sum of the heat delivered to the surface from the liquid reservoir by liquid as it is brought up from the reservoir temperature T_R to the surface temperature T_W.

$$\dot{m}_\infty di_\infty= h\ (T_R-T_W)dA_W+i_s\dot{m}_\infty dY_{F\infty} \tag{15}$$

h is the heat transfer coefficient in the liquid, and i_s is the sensible enthalpy change of liquid equal to $C(T_W-T_R)$ where C is the liquid specific heat. The total heat of evaporation i_f is the sum of i_s and the latent heat of vaporization i_{vap} which is the amount of heat needed to vaporize a unit mass of liquid at temperature T_W to vapor at temperature T_W.

Eliminating dA_W from Eqs. (14) and (15) and using Eq. (13),

$$h(T_R-T_W) = h_g(T_W-T_\infty) + h_D(Y_{FW}-Y_{F\infty})(i_f-i_s) \tag{16}$$

which beoomes with further minor manipulation,

$$C_g(T_R-T_W) = \left[\frac{hg}{h_g+h}\right]\left[C_g(T_R-T_\infty) + [\frac{h_D C_g}{h_g}] (Y_{FW}-Y_{F\infty}) i_{vap}\right] \tag{17}$$

C_g, here, is the gas phase specific heat. i_{vap} is placed for the difference (i_f-i_s).

If the liquid-phase is comparatively better mixed than gas-phase, $h>>h_g$ so that the right hand side of Eq.(17) nears zero and, hence, $T_R \simeq T_W$. If the liquid were flowing, T_R gradually approaches T_W in a finite flow length. If, on the other hand, the liquid were standing still, the approach of T_R to T_W will occur in a finite time. After the equality $T_R \simeq T_W$ is reached thus either through space or time, no further heat transfer occurs between the liquid and its surface. Substituting $T_R \approx T_W$ into Eq. (16) (or Eq. (17)),

$$h_g(T_W-T_\infty) = - h_D(Y_{FW}-Y_{F\infty}) i_{vap} \tag{18}$$

or

$$C_g(T_W-T_\infty) = - [\frac{h_D C_g}{h_g}] (Y_{FW}-Y_{F\infty}) i_{vap} \tag{18a}$$

The total evaporation heat is thus supplied under these conditions solely by the gas phase. Note that $[h_D C_g/h_g]$ in Eq. (18a) is a function of the Lewis number $Le \equiv D_g/\alpha_g$ and is equal to unity if the Lewis number is unity. (D_g is the mass diffusity of fuel vapor in air (cm^2/sec) and α_g is thermal diffusity of the gas-phase ($cm^2/sec \equiv K_g/\rho_g C_g$).

Rewriting Eq. (16)

$$h(T_R-T_W) = (h_g/C_g) (C_g(T_W-T_\infty)+ [\frac{h_D C_g}{h_g}] (Y_{FW}-Y_{F\infty})i_{vap}) \tag{19}$$

The left hand side of this equation is the heat supplied by the reservoir to its surface. The right hand side is the heat expenditure. Whereas the quantity

$[h_g/C_g]$ is a sort of mass transfer coefficient (gm/cm^{2}sec), the two quantities in the second bracket of RHS of Eq. (19) are enthalpy differences of the problem. Depending upon the temperatures of the reservoir, surface and ambience, and the ambient fuel mass fraction, a variety of situations of heating and cooling arise from Eq. (19) as shown in Figure 3.

What does all this have to do with pool burning under reduced gravity? First, allowing the upper plate of our parallel plate duct to be placed far away from the lower plate, we realize the pool conceptually. Note that no where in the duct problem have we stipulated the duct dimension, just to facilitate the adoption of the duct description to the pool description.

Second, gravity enters our problem, rather profoundly, through its influence on the heat transfer coefficients both in the liquid (h) and in the ambient gas-phase (h_g).

The family of problems delineated in Figure 3 have a host of both scientific and practical applications. These range from humidification, defogging, and such other environmental control processes to a host of chemical process operations including the generation of vapors and their combustion.

The evaporative mass transfer rate itself is given by resolving Eq. (16) to

$$\dot{m}''_F = [h(T_R-T_W)+h_g(T_\infty-T_W]/i_{vap} \tag{20}$$

That is, the evaporative heat sink $\dot{m}''_F i_{vap}$ at the interface is equal to the sum of steady state convective heat fluxes from the reservoir and from ambience to the evaporating surface. The strong influence of gravity on h and h_g and hence on the mass flux $\dot{m}''_F$ is obvious through our other past and future considerations of this project.

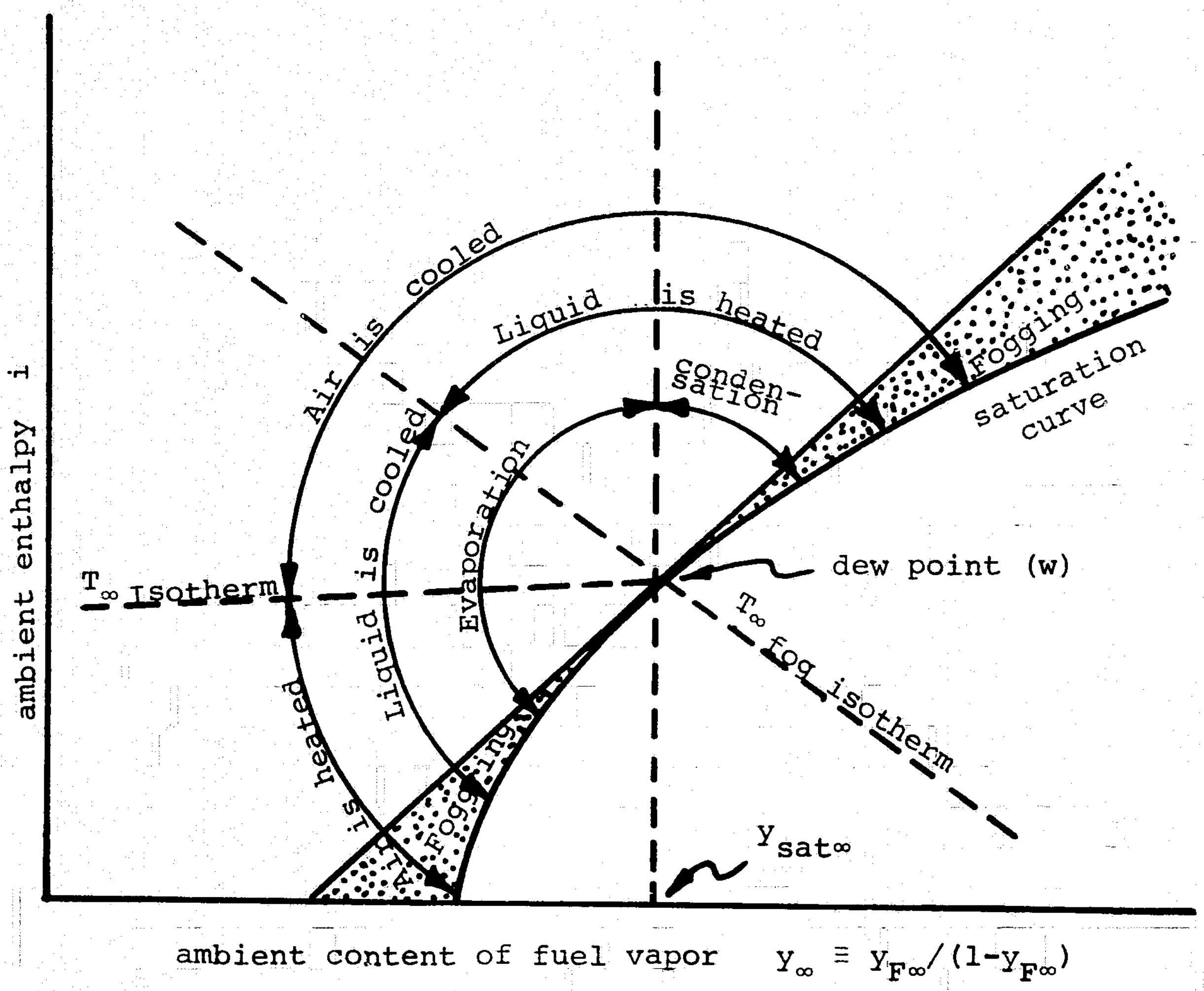

Figure 3 The Interface state (w) is determined by the ambient state (∞) (Adapted from Bosjnakovic & Blackshear [6])

CHAPTER V

TRANSIENT DISPERSION OF FUEL VAPORS INTO THE QUIESCENT ATMOSPHERE

Lapse Rate:

Naturally generated convection is absent in a stable atmosphere. As such an atmosphere becomes gradually more stable, it will increasingly tend to suppress any circulation produced by other sources. The vertical density gradient $\partial\rho/\partial y$ determines the atmospheric stability. When an element of the atmosphere is displaced upward to expand adiabatically against the sole constraint of the surrounding atmospheric pressure,then if the density of the element is greater than that of the ambience, the element will tumble down to its original elevation thus stabilizing the atmosphere. Because the vertical pressure gradient of the displaced element is the same as that of the ambient atmosphere, the density gradient is determined by the vertical temperature gradient (i.e., the lapse rate). Adiabatic lapse rate for a dry air atmosphere is dependent upon the graviational constant, gas constant and the ratio of specific heats according to

$$\frac{\partial T}{\partial y} = -\frac{g}{R}\frac{(k-1)}{k} \tag{21}$$

This relation is obtained [7] by considering a perfect gas (pv=RT) undergoing an adiabatic expansion process (pv^k=constant) in a situation where the pressure change with height y is given by $dp=\rho g dy$. The derivation of Eq. (21) is clearly presented by Prandtl and Tietjens [7]*. Substituting, for air the ratio of

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*The following steps are involved.

$$(T/T_1) = (p/p_1)^{(k-1)/k}$$

$$dy = (RT/g)(dp/p) = (RT_1/gp_1^{(k-1)/k})\,p^{-1/k}\,dp$$

$$y-y_1 = (RT_1k/g(k-1))\,(1-(p/p_1)^{(k-1)/k})$$

$$y-y_1 = (RT_1k/g(k-1))\,(1-T/T_1)$$

$$\therefore\ \partial y/\partial T = -Rk/g(k-1)$$

specific heats k=1.405 and molecular weight M=29 gm/gm-mole, Eq (21) gives the standard adiabatic dry air lapse rate of -3°C per 1000 ft elevation. Lapse rates greater than this value will give a stable atmosphere. Note from Eq. (21) that as gravity is reduced, the lapse rate approaches zero thus indicating a stabler atmosphere. There are no experiments, to the knowledge of this writer, to verify and confirm this matter.

Convection of air in an enclosure may be produced not only by an unstable atmosphere, but also by transverse temperature (and/or density) gradients, mechanical devices such as fans and blowers and by air jets. If a fuel gas or vapor is introduced into such an enclosure, the mixing resulting from the convection, no matter how this convection is produced, rapidly achieves a uniform composition mixture in the entire space. Now visualize an enclosure in which all sources of convection are deliberately precluded. Suppose a heavier gas at the bottom or a lighter gas at the top is introduced at a very feeble rate into the chamber. Mixing occurs then very slowly under the combined influence of molecular diffusion and weak convection due to displacement of air by the foreign gas. Stratification may occur to make possible high composition gradients [8,9]. If the gas introduced is combustible, flammable concentrations may develop in a belt of space whose width and location will vary with time.

Pool Evaporation:

As our pool evaporates at a rate dictated by the heat transfer to the interface, the vapors are dispersed into the atmosphere. In Chapter C IV we have described a situation in which heat transfer is purely convective from both the gas and liquid-phases and deduced an equation for the evaporation rate $\dot{m}''$ (Eq. 20). If one chooses to impose by external control on the gas-phase side of the interface an additional heat flow of thermal radiation (I cal/cm^{2}sec), then Eq. (20) is slightly altered as below.

$$\dot{m}''_F = (h(T_R - T_W) + h_g(T_\infty - T_W) + I)/i_{vap} \tag{22}$$

If I were negative, it would imply a reradiative loss suffered by the surface, or an extraneously caused heat sink at the surface.

The dispersion process itself involves diffusive and convective contributions. If gravity is present, it will aid the convective dispersion by invoking momentum terms associated with temperature and concentration differences. Denoting the mole fraction by X, height by y, time by t, diffusion coefficient by D and mass transfer velocity by v, the assumed one-dimensional dispersion problem is described by the following equations.

$$D \frac{\partial^2 X}{\partial y^2} = v \frac{\partial X}{\partial y} + \frac{\partial X}{\partial t} \tag{23}$$

$$\begin{array}{ll} X\ (y,0) = 0 & t \leq 0,\ y \geq 0 \\ X(\infty,t) = 0 & t \geq 0,\ y \to \infty \\ \partial X/\partial y|_{o,t} = (v/D)(X(o,t)-1) & t \geq 0,\ y=0 \end{array}$$

Valentine and Moore [8] solved this problem numerically. Kanury [9] obtained a closed-form solution for $X(\eta,\tau)$ where the nondimensional distance η and time τ are defined by $\eta = vy/D$ and $\tau = v^2 t/D$. The main finding was that when the leak rate is high, the time required to attain a prescribed critical concentration at a given height is independent of the diffusity; and the width of the flammable domain is nearly independent of time. When the leak rate, on the other hand, is low, the critical time at any height is independent of the evaporation rate; and the width of the flammable domain is significantly dependent on time.

The significant questions that remain unresolved are: how would gravity tamper with the stability of the atmosphere? How would gravity enter into the dispersion problem described by Eqs.(22) and (23)? What precisely would be the role played by gravity in determining the time to attain flammability limits at any given height and the width of the flammable belt? Only further analysis and experiments hold the answers.

CHAPTER C VI

FORMATION OF COMBUSTIBLE SPACE IN THE GAS-PHASE

In the previous chapter we have discussed the general principles governing the dispersion of fuel vapors produced at the liquid surface under stable atmospheric conditions. The mole fraction X of fuel vapor penetrates into the gas-phase as a function of time according to the solution of Eq. (23). This solution is

$$X(\eta,\tau) = (\tau/\pi)^{1/2} \exp[-(\tau/4)(\eta/\tau-1)^2] + (1/2) \operatorname{erfc} [(\tau^{1/2}/2)(\eta/\tau-1)]$$

$$-(1/2)(1+\eta+\tau)\cdot\exp\eta\cdot \operatorname{erfc} [(\tau^{1/2}/2)(\eta/\tau+1)] \quad (24)$$

where $\eta \equiv vy/D$ and $t \equiv v^2 t/D$; v is the evaporation velocity; y is the height in the gas-phase above the source surface; t is time; and D is fuel vapor diffusivity in air. η and τ, thus, are nondimensional vertical distance and time respectively. The ambient atmosphere is assumed to be composed of quiescent air.

The supply velocity v is controlled by one of three possible ways. First: the fuel gas vapor may be released at the source surface to leak at a metered velocity of v. Second: the fuel vapor may be produced by imposing an externally controlled thermal radiation flux upon the surface of a liquid fuel. Since the atmosphere is quiescent, there will occur no convective heat transfer.Thus the evaporation rate equation (Eq. (22)) simplifies to

$$\dot{m}''_F \equiv \rho_F v = [I-h\ (T_W-T_R)]/i_{vap} \quad (25)$$

If the liquid-phase mixing is minimal, this equation can be manipulated to the following familar alternative form.

$$\dot{m}''_F = \rho_F v = I/([1+h\ (T_W-T_R)/I]\ [i_{vap}]) \quad (26)$$

The third method of producing the interfacial normal velocity v is to allow convective heat transfer to occur so that the numerator of Eq. (26) is $h_g(T_\infty - T_W)$. If this gas-phase convective heat transfer were to occur naturally (i.e., free convection), $h_g \propto g^n$ where n lies between 1/4 and 1/2 depending upon the laminar or turbulent nature of the flow. Gravity exerts its primary influence on the dispersion problem through this heat transfer mechanism. We will discuss this issue further later in this chapter.

For small values of nondimensional time, Eq. (24) may be approximated to the following form

$$(\pi\eta^2/\tau)^{1/2} X(\eta,\tau) = \beta_o^{1/2} \quad ; \quad \tau \ll 1 \tag{27}$$

where β_o is so weakly dependent on η and τ that it may be considered as a constant. For large values of time, on the other hand,

$$(\pi\eta/\tau)^{1/2} X(\eta,\tau) = \beta_\infty^{1/2} \quad ; \quad \tau \gg 1 \tag{28}$$

where β_∞, again, is a weak function of η and τ. Substituting the definitions of η and τ, Eqs. (27) and (28) give, for small times,

$$X(y,t) = (\beta_o Dt/\pi y^2)^{1/2} \tag{29}$$

and, for large times.

$$X(y,t) = (\beta_\infty vt/\pi y)^{1/2} \tag{30}$$

If X_ℓ and X_u are mole fractions corresponding respectively to the lower and upper limits of flammability of the fuel vapor in air, then Eqs. (29) and (30) can be used to obtain the thickness $\Delta \equiv (y_\ell - y_u)$ of the flammable space as dependent upon time. For small times,

$$\Delta = (\beta_o Dt/\pi)^{1/2} (X_\ell^{-1} - X_u^{-1}) \tag{31}$$

and, for large times,

$$\Delta = (\beta_\infty \; vt/\pi) \; (X_\ell^{-2} - X_u^{-2}) \tag{32}$$

The preceeding relationships have some important implications that are both scientific and practical. Some of these implications are discussed below.

From Eq. (29) we note that for small times, the despersion is independent of the evaporation velocity v and that the species diffusivity alone governs the composition distribution. This result is not unexpectable, for the governing differential equation $D\partial^2X/\partial y^2 = v\partial X/\partial y + X/\partial t$ would then have been simplified by vanishing the convective term and the solution will be in the form $X(y,t) = f(y^2/Dt)$. Note that the time t^* required to attain a prescribed fuel concentration X^* at a given height y^* is given by Eq. (29) as

$$t^* = \pi y^{*2} \; X^{*2}/\beta_o D$$

independent of the injection velocity. The time t^* is shorter for a low molecular weight fuel vapor (i.e., for a high diffusivity species). This relation seems to be aminable for verification by earth based g=1 experimentation.

At large times, however the governing differential equation may be simplified to $v\partial X/\partial y + \partial X/\partial t = 0$ so that the solution takes the form $X(y,t) = f(y/vt)$. Thus

$$t^* = \pi y^* \; X^{*2}/ \; \beta_\infty v$$

so that the time characteristic under consideration is independent of the diffusive nature of the fuel species but depends strongly on the evaporative velocity.

If the evaporation rate were determined by free convective heat transfer with the absence of any externally imposed heat flux, $v \propto h_g \propto g^n$ and, hence, $t^* \propto g^{-n}$, with n 1/4-1/3. As the gravity level is gradually reduced, the time to attain a particular concentration at a particular location will rapidly increase. At a gravity level of 10^{-6}g, for example, the time will be 30 to 100 times longer than the time at normal gravity. At a level of 10^{-4}g, it will be 10 to 20 times longer than the normal gravity time. In the limit of gravity tending to zero, the time t* tends to infinity, for then the convectively governed evaporation itself ceases altogether.

In an actual experiment at very low gravity level, we expect that the ambient pressure and temperature determine the partial pressure of the fuel vapor at the fuel surface and dispersion occurs through molecular diffusion and Eqs. (27), (29) and (31) describe the behavior.

Figure 4 depicts these observations on the characteristic time t*.

Turning our attention to the time-dependent location of the combustible belt of space and its width, we employ Eqs. (29) - (32). For small times, the height at which the concentration corresponds to the lower flammability limit is given by

$$y_\ell = (\beta_o Dt/\pi X_\ell^2)^{1/2}$$

and, for large times,

$$y_\ell = (\beta_\infty vt/\pi X_\ell^2)$$

A plot of $y_\ell(t)$ based upon these two limiting relations is shown in Figure 5.

Note also that the width of the combustible space Δ varies in proportion to $t^{1/2}$ at small times and to t at large times. The independence of Δ on v at small times and on D at large times continues to hold.

Other observations are also possible. The process of vapor dispersion above the pool to form combustible mixture is obviously one that has many practical uses in both combustion and safety as well as in chemical process industry. The precise role played by gravity in this problem is less than

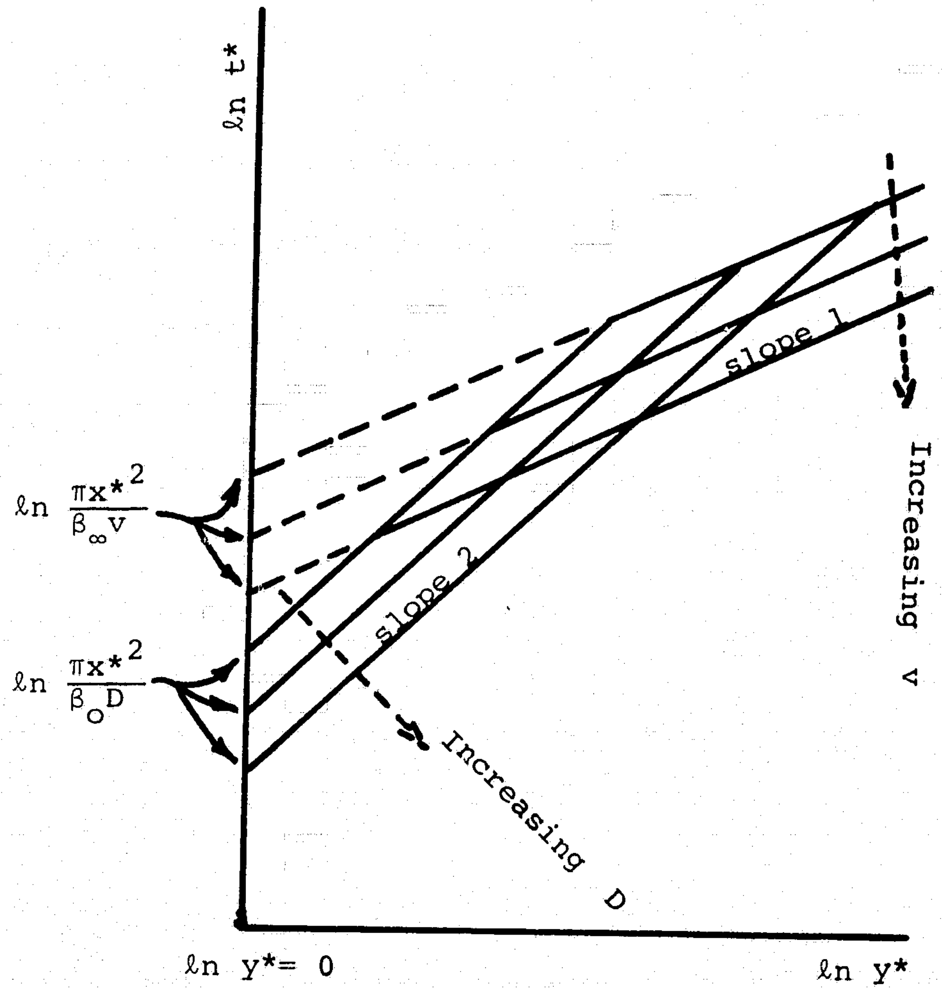

Figure 4 Time t^* to attain a prescribed concentration x^* at a given height y^* as dependent upon fuel vapor diffusivity D and evaporation velocity v.

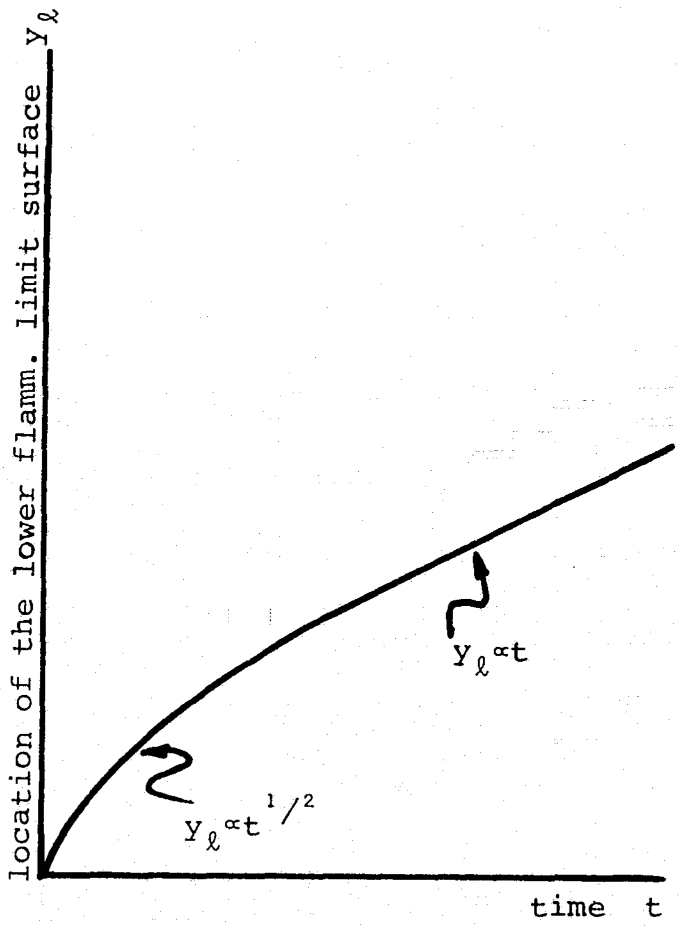

Figure 5 Location of the 'Lower Flammability Limit Surface' as a function of time

clear at this time with the available simple analyses and the nonexistent experimental data. While acknowledging that the theory described above is by no means complete, nor sophisticated, we do hope to have demonstrated the need to experimentally measure the location and extent of the combustion domain over pools evaporating, without combustion, under controlled low-gravity conditions.

Note, however, that in this entire discussion we have dealt with the lower and upper flammability limits as though they are independent of the intensity and direction of gravity. Berlad points out quite convincingly that these limits depend, perhaps strongly, on the instabilities induced by gravity. Such dependencies have to be incorporated into our model at some later date when they are better understood than today.

CHAPTER C VII

IGNITION OF FUEL POOLS THAT ARE INITIALLY ABOVE THEIR FLASH POINT

Upon evaporation of a pool of liquid fuel at an initial temperature which is above the flash point, the vapors disperse into the quiescent atmosphere producing a temporally propagating combustible space. Our goal is to explore the ignition characteristics of the combustible space when different ignition sources [10] are presented and to find those aspects of the problem in which gravity might play a role.

<u>Ignition of a Heated Wire</u>:

Suppose a horizontal wire of diameter 2a is kept at a steady and uniform temperature T_w by passing electrical energy through it. Let the surroundings of this wire be composed of the fuel + air reactant mixture above the liquid fuel pool. T_o is the ambient temperature (the mixture composition at the fixed location of the wire, of course, varies with time as described in the chapters C V and C VI. Due to the temperature differential $(T_w - T_o)$, a free convective boundary layer of average thickness b is established around the heated wire. (The transience of establishment of this boundary layer is ignored here.) Heat is transferred across the boundary layer. Heat is also generated in the layer due to the preignition chemical reactions. Ignition may be presumed to have occurred when the heat generation rate approaches, in magnitude, the heat loss rate so that subsequent perpetuation of the combustion reaction can occur independent of the heated wire. Thus, if $\dot{W}_o'''$ is the volumetric reaction rate corresponding to the wire temperature (with neglected reactant depletion effects), ignition will occur if

$$\Delta H \dot{W}_o''' \, [\ell \pi (2a+b) b] \geq K_g \left(\frac{T_w - T_o}{b}\right) [\ell \pi (2a+b)] \qquad (33)$$

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ΔH is heat of the preignition reactions. K_g is the gas-phase thermal conductivity. ℓ is the wire length. (2a+b) is the effective diameter of the reactive layer; the square bracketted terms respectively are the gas layer volume on the left hand side and the surface area on the right. Thus, ignition is possible if

$$\Delta H \hat{W}_o''' \, b/K_g \geq (T_w - T_o)/b \tag{34}$$

Noting that the boundary layer thickness b is related to the Nusselt number Nu through the heat transfer coefficient h, ($Nu \equiv h2a/K_g$, $b = K_g/h$, and hence, $b \equiv 2a/Nu$),

$$a^2 \geq \frac{K_g (T_w - T_o) Nu^2}{4 \Delta H \hat{W}_o'''} \tag{35}$$

If we extend this analysis to free convective flow, $Nu \approx 0.525\,(GrPr)^{1/4}$, so that,

$$a^2 \geq \frac{K_g (T_w - T_o)}{4 \Delta H \hat{W}_o'''} (0.525)^2 \, (Gr\ Pr)^{1/2} \tag{36}$$

The Grashof and Prandtl numbers are defined by

$$Gr \equiv g(2a)^3 \, \beta (T_w - T_o) \, \rho_g^2/\mu_g^2 \quad ; \quad Pr \equiv \mu_g C_{pg}/K_g$$

where g is gravitational constant, β is volumetric expansion coefficient, ρ_g is gas-phase density, μ_g is gas-phase dynamic viscosity and C_{pg} is the specific heat of the gas-phase. Substituting these definitions in Eq. (36) and resolving for the wire size,

$$a \geq (0.525)^4 \, \frac{2^3}{4^2} \, \frac{K_g C_{pg} \rho_g^2}{\mu_g} \cdot \frac{g\beta (T_w - T_o)^3}{(\Delta H \hat{W}_o''')^2}$$

which may be rewritten as below

$$a \geq (0.525)^4 \frac{2^3}{4^2} \left(\frac{\alpha_g}{\nu_g}\right) \left[\frac{\rho_g C_{pg} (T_w - T_o)}{\Delta H \dot{W}_o'''}\right]^2 g\beta\,(T_w - T_o) \tag{37}$$

According to this equation, ignition is possible with a thinner wire if the gas conductivity, volumetric heat capacity, temperature difference, and gravity are lower and if the viscosity, heat of combustion and preignition reaction rate are higher. The reasons underlying are simple; any circumstance which would reduce the heat loss rate relative to the generation rate is conducive to easier ignition.

An interesting dilemma which arises here is this: if everything else is kept fixed except the gravity level g, ignition must be possible at $g \to 0$ by an infinitesimally thin wire (or particle). This expectation is a consequence of the then reduced convective flows. There must, in actuality however, exist a breakdown of the relation given by Eq. (37) due to drastic departure of the hypothesis used to derive it from the events culminating in ignition. This matter could only be settled by prolonged, programmed low gravity experimentation.

We can further extend Eq. (37) to deduce a relation between the time required to produce ignition by a certain size wire located at a certain height. From Chapter CVI the time to reach the lower flammability limit X_ℓ at any given height y above an evaporating pool is known. Assuming that (a) the reaction rate $\dot{W}_o'''$ becomes significant as the fuel mole fraction X approaches X_ℓ, the lower flammability limit, (b) the ambience is composed of pure oxidant (the presence of inerts such as nitrogen can be dealt with quite easily, if needed) and (c) the preignition reactions are simple

$$\dot{W}_o''' \simeq k\, f^{n/2} (1-f^{1/2})^m\, e^{-E/RT} \tag{38}$$

where f is $(\beta_o Dt/\pi y^2)$ for short times and is $(\beta_\infty vt/\pi y)$ for long times. k is the frequency factor $(gm/cm^3 sec)$, n and m are orders of the reaction respectively with fuel and with oxidant, E/R is activation temperature. The temperature in the Arrhenius exponential is to be chosen somewhere between the wire and ambient temperatures. Furthermore, the oxidant term in this equation may be taken to be unity for a first order approximation. Substituting this simplified rate equation in Eq. (37),

$$a_{cr} \approx (0.525)^4 \frac{2^3}{4^2} \left(\frac{\alpha_g}{\nu_g}\right) g\beta\,(T_w - T_o)\left[\frac{\rho_g C_{pg}(T_w - T_o)}{\Delta H\, k e^{-E/RT}}\right]^2 \frac{1}{f^n} \tag{39}$$

The value of n lies somewhere between 1/2 and 1. Equation (39) indicates the time to achieve ignition conditions at any height y with a given wire. Since f is nearly independent of gravity for the small time dispersion solutions, a_{cr} is proportional to g. For long-time dispersion solutions, however, f is proportional to the velocity of vaporization which is a function of gravity as $g^{1/4 \text{ to } 1/3}$, thus, $a_{cr} \propto g^{7/8 \text{ to } 2/3}$.

Ignition by Flames:

If a pilot flame of thickness $2a$ is held in the combustible mixture, and if this thickness is greater than a critical value the reactive heat generation dominates dissipation by conduction and convection and leads to the evolution of a self-propagating flame front. Combustion literature shows that the critical half-thickness a_{cr} of the pilot flame is approximately of the order of the flame thickness δ_f characteristic of the mixture.

$$a_{cr} \approx \delta_f$$

Equating the orders of magnitude of heat conduction across a propagating flame front, convection due to propagation, and heat generation due to combustion, the following well-known relations are obtainable.

$$\delta_f \simeq \frac{\alpha_g}{U_o} \quad , \quad \delta_f \simeq \left[\frac{K_g(T_f-T_o)}{\Delta H\hat{W}_o'''}\right]^{1/2} \quad , \quad \delta_f \simeq \frac{\rho_g U_o C_{pg}(T_f-T_o)}{\Delta H\hat{W}_o'''} \tag{40}$$

Here α_g is thermal diffusivity of the gases, U_o is the fundamental flame speed, T_f and T_o are respectively the flame and initial temperatures, and C_{pg} is the specific heat of the gases. Thus,

$$a_{cr} \simeq \left[\frac{K_g(T_f-T_o)}{\Delta H\hat{W}_o'''}\right]^{1/2} \tag{41}$$

High conductivities, high flame temperatures and low volumetric heat release rates thus require a larger pilot ignition source. One must further note that (since $\delta_f \propto 1/\rho_g U_o$ and since $U_o \propto P^{(q-2)/2}$ and $\rho_g \propto P$ where P is the ambient gas pressure and q is the overall order of the flame reaction ($q=n+m$), $a_{cr} \propto P^{-q/2}$. A low ambient pressure requires a larger pilot flame.

Once again we can substitute Eq. (38) in (41) to obtain the size of pilot flame required at any given height y to produce ignition in a time of the order t.

$$\bar{a}_{cr} \simeq \left[\frac{K_g(T_f-T_o)}{\Delta H k e^{-E/RT}}\right]^{1/2} \frac{1}{f^{n/4}} \tag{42}$$

(Recall that n is the order of the reaction with respect to the fuel.) Smaller allowed ignition times at large distances from the pool surface require larger pilot flames. Inferring from the dependency of f on g, the critical flame thickness is either uninfluenced by g(from short-time dispersion solutions) or weakly influenced ($a_{cr} \propto g^{-0.03 \text{ to } -0.10}$ from long-time dispersion solutions). This deduction is in considerable contrast with the hot-wire result (Eq. (39)) both in the direction and intensity of the gravitational influences. The primary reason, of course, is the free convective heat loss in gas-phase.

Ignition by Electric Sparks:

Ignition may also be accomplished by striking an electric spark between electrodes located in the combustible mixture. To minimize the ignition energy while avoiding quenching effects, the electrodes are to be placed at a separation distance which is approximately equal to the quenching distance of the mixture. The quenching distance is known to be about twice the flame front thickness δ_f. To a first approximation, the minimum ignition energy is of the order of energy needed to raise a sphere of gas mixture of diameter equal to quenching distance from the initial to flame temperature. Thus

$$E_{min} \simeq \frac{\pi(2\delta_f)^3}{6} \rho_g C_{pg}(T_f - T_o) \tag{43}$$

Substituting for δ_f, $E_{min} \simeq 4\pi K_g(T_f - T_o)\delta_f^2/3U_o$, a relation of known proportionality of $E_{min} \propto \delta_f^2$. Complete elimination of δ_f yields

$$E_{min} \simeq \frac{4\pi}{3} \rho_g C_{pg} \left[\frac{K_g}{\Delta H \dot{W}_o'''}\right]^{3/2} (T_f - T_o)^{5/2} \tag{44}$$

from which substitution of Eq. (38) gives

$$E_{min} \simeq \frac{4\pi}{3} \rho_g C_{pg} \left[\frac{K_g}{\Delta H k e^{-E/RT}}\right]^{3/2} \frac{1}{f^{3n/4}} (T_f - T_o)^{5/2} \tag{45}$$

Once again we note that at small times t, and large distances, the minimum required energy for ignition is higher. $E_{min} \propto g^o$ for small-times and $\propto$ $g^{-0.1 \text{ to } -0.25}$ for long-times.

Concluding Remarks:

The brief analyses presented above become useful not only to deduce some preliminary expectations of the role played by gravity in the ignition process but also to develop the most convenient technique of producing ignition in the Spacelab experiment. Two brief comments are needed here in concluding this chapter.

First, it is a well-known matter that for successful ignition to occur, the combustible space width Δ has to be larger than the characteristic quenching distance of the mixture. This requirement combines the physical dispersion process of the vapor with the physico-chemical process of combustion of the mixture. Knowing Δ from the previous chapter and quenching distance from Eq. (40) of this chapter the substained ignition is possible if

$$\Delta \geq 2\delta_f \tag{46}$$

δ_f being given by Eq. (40) as equal to $K_g/\rho_g C_{pg} U_o$, or to $(K_g(T_f-T_o)/\Delta H\hat{W}_o''')^{1/2}$, or to $(\rho_g C_{pg} U_o (T_f-T_o)/\Delta H\hat{W}_o''')$. The height at which the lower flammability limit is reached at any given time t is given by

$$\begin{aligned} y &\geq 2\delta_f/(1-X_\ell/X_u) && \text{small-times} \\ &\geq 2\delta_f/(1-X_\ell^2/X_u^2) && \text{long-times} \end{aligned} \tag{47}$$

the condition for fulfilling the quenching considerations. If an ignition source is held too close to the evaporating surface, no matter what the nature of this source is, the composition gradients are so severely high that the combustible space width Δ is much smaller than the quenching distance and persistent ignition is not possible. The dependence of δ_f on various physicochemical properties of the problem will enable the choice of the location of ignition source to achieve ignition via Eqs. (46) and (47). Since $\delta_f \approx (\hat{W}''')^{-1/2}$, $\dot{W}''' \approx f^{n/2}$, $f \approx v^o$ (short-times) or v for long-times, $v \approx g^{1/4 \text{ to } 1/3}$ and since $n \simeq 1/2$ to $1/3$, we infer $y \approx g^o$ from short-time dispersion solutions and $y \approx g^{-0.03 \text{ to } -0.10}$ from long-time solutions.

Second, in this entire matter of ignition and flammability limits considered in this chapter and the previous one, we did not make a scrupulous examination of the definition of 'flammability limits'. Berlad [11] describes how extinction

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limits of premixed flames depend upon the direction of flame propagation with respect to the gravity level and gravity vector. Some detailed implications of Berlad's arguments related to the role of gravity in determining flammability limits have to be incorporated into our X_ℓ and X_u values used.

Finally, the dispersion results employed in this chapter are only the approximate ones. This is done mainly to illustrate the technique of analyzing the space, time, vapor-nature, ignition source relations. The complete, even if complex, general dispersion solution could be employed in a more detailed treatment if time and computational facilities permit and if the generality is indeed required. It is obvious from the preceeding derivations that the long-time solution is really the one that would best benefit from low-g studies, for then the transpiration velocity v, which is strongly dependent upon g, comes into play.

CHAPTER C VIII

IGNITION OF FUEL POOLS THAT ARE INITIALLY BELOW THEIR FLASH POINT

Consider a fuel pool whose initial temperature is below its flash point. Suppose an electrically heated wire, to be considered as a cylinder of diameter d, is placed parallel to the pool surface at a distance δ from the surface in the gas phase. Let the power be switched on at time zero. A transient free convection flow is thus initiated in the gas-phase surrounding the cylinder. Typically expected temperature field is sketched in Figure 6. As the flow develops and thermal wave penetrates, a time will come beyond which the liquid surface gets into thermal contact with the heat source.

As one marches along the liquid surface in a direction perpendicular to the cylinder axis, one encounters a gradually decreasing heat flux to the surface, as indicated in Figure 7. Due to the consequent temperature gradient along the liquid surface, surface-tension gradients arise to produce flow in the condensed phase. Under the influence of these surface-tension forces, and buoyancy, inertia and viscous forces, two cylindrical cells are produced in the liquid as shown in Figure 8. These cells cause the liquid surface to swell upwards directly under the heated cylinder.

Given this situation, to determine the flow patterns, the heat transfer distribution, the resultant production of fuel vapors, their dispersion in the gas-phase and ignition of the mixture so formed constitute an important problem both in science and practice.

Our considerable search into the engineering, physics and chemistry literatures pointed out only one reference to this problem [22]. We therefore attempt in the following a brief dimensional analysis to identify the process components of the problem.

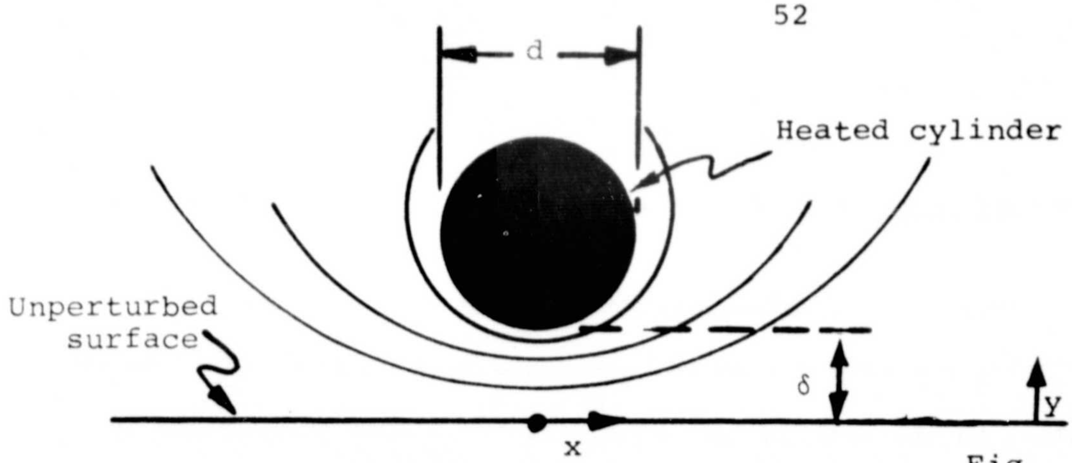

Fig. 6

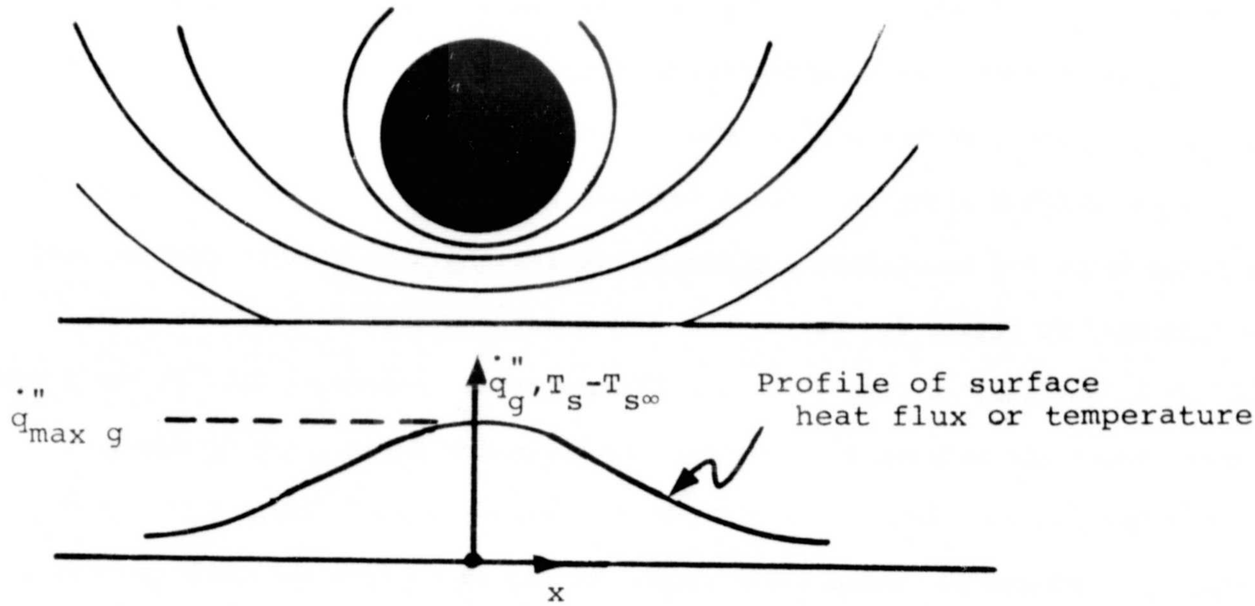

Fig. 7

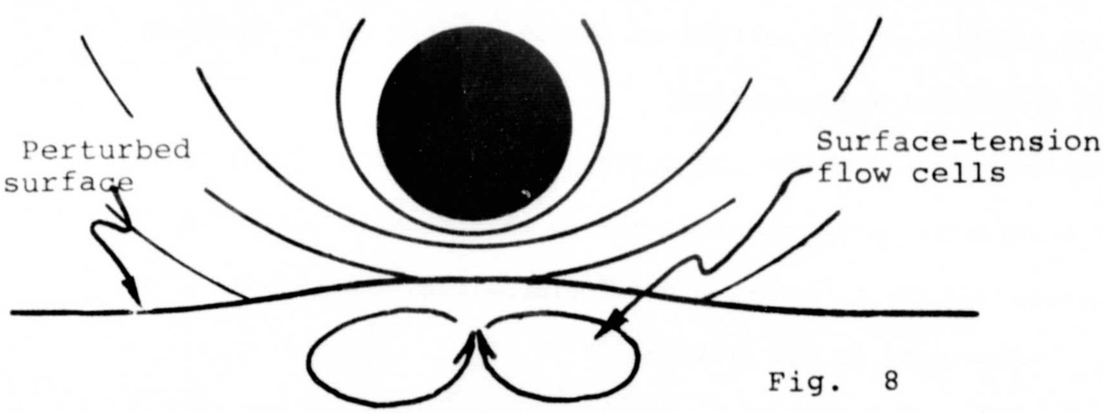

Fig. 8

To a first approximation, it seems reasonable to scale the vertical dimensions with respect to δ (the distance between the lower surface of the cylinder and the unperturbed liquid surface) and the horizontal dimensions with respect to the cylinder diameter d. We will also assume that δ is small enough in magnitude that a sure thermal contact exists between the cylinder and liquid surface via the free convective flow of the gas-phase. Without seeking to obtain a complete solution at this time, we may expect the distribution of temperature along the liquid surface to follow a relation such as the following.

$$\frac{dT}{dx} = \frac{\dot{q}''_{max\ g}}{K_g} e^{-(x/d)^2} \tag{48}$$

$\dot{q}''_{max_g}$ is the maximum heat flux from the cylinder to the liquid which occurs at x = 0, i.e., directly below the cylinder. K_g is the gas phase thermal conductivity.

Given this surface temperature distribution, a surface-tension gradient is set up and a consequent flow is developed. Recalling x and y are coordinates respectively along and normal to the liquid surface, we can look at the flow in the condensed phase as determined by a balance between the surface-tension, viscous and buoyancy forces. This scrutiny is somewhat parallel to, if not the same as, the basic analyses conducted in Chapter C I. The condensed-phase convective cells are depicted in Figure 8. There will, of course, be two cylindrical cells, as shown. From Eq. (48) it is expectable that the extent of the cell in x-direction will be of the order d. Denoting the y-directional cell dimension by Δ, a balance among the participant forces results in an estimation of the involved velocities.

Equating the viscous and surface-tension effects,

$$\mu \frac{\partial u}{\partial y} \frac{\pi d^2}{4} \simeq \frac{d\sigma}{dx} \frac{\pi d^2}{4} \tag{49}$$

where μ is liquid viscosity, u is parallel velocity and σ is surface tension. Rewriting $d\sigma/dx$ as $(d\sigma/dT)(\partial T/dx)$, Eq. (49) gives

$$u \simeq \frac{\Delta}{\mu} \frac{\sigma}{d} \simeq \frac{\Delta}{\mu} \frac{d\sigma}{dT} \frac{dT}{dx} \tag{50}$$

Equating viscous and buoyancy forces,

$$\mu \frac{\partial v}{\partial x} \pi d\Delta \simeq g(\rho_F - \rho_{F\infty}) \frac{\pi d^2}{4} \Delta \tag{51}$$

where ρ_F is the density of the perturbed liquid and $\rho_{F\infty}$ is that of the unperturbed liquid. This relation boils down in magnitude to

$$v \simeq \frac{gd^2}{4\mu} (\rho_F - \rho_{F\infty}) \tag{52}$$

From continuity, $u/d \simeq v/\Delta$, so that

$$\Delta \simeq \left[\frac{gd^2}{4\mu} (\rho_F - \rho_{F\infty}) \frac{\mu\ d}{d\sigma/dT} \frac{K_g e^1}{\dot{q}''_{max\ g}}\right]^{1/2} \tag{53}$$

and

$$u \simeq \left[\frac{gd^3}{4\mu^2} (\rho_F - \rho_{F\infty}) \frac{d\sigma/dT \cdot \dot{q}''_{max\ g}}{K_g e^1}\right]^{1/2} \tag{54}$$

We can also obtain an order of magnitude estimation of the normal velocity v by equating the convective and conductive heat fluxes in the condensed phase.

$$v \frac{\partial T}{\partial y} \frac{\pi d^2}{4} \simeq \frac{K_F}{\rho_{F\infty} C_{PF}} \frac{\partial^2 T}{\partial y^2} \pi d\Delta$$

so that

$$v \simeq \frac{\alpha_F}{4d} \tag{55}$$

where $\alpha_F \equiv K_F / \rho_{F\infty} C_{pF}$ is the thermal diffusivity of the liquid.

We further note that the maximum heat flux is given approximately by

$$\dot{q}''_{max\ g} \simeq \frac{K_g}{\delta} \left(T_{wire} - T_{s\ max}\right) \tag{56}$$

and that the mass transfer rate is proporatioal to the heat transfer rate via the latent heat of vaporization L.

$$\dot{m}'' \simeq \frac{\dot{q}''_{max\ g}}{L} e^{-(x/d)^2} \tag{57}$$

In Eq. (56) $T_{s\ max}$ is the maximum surface temperature which occurs directly under the wire, i.e., at x=0. Out of the relations given by Eqs. (52), (54)-(57) evolve the nondimensional parameters which describe the considered problem. These are:

First Peclet Number	$Pe1 \equiv \frac{vd}{\alpha_F}$
Marangoni Number	$Ma \equiv \frac{d\sigma}{dT} \cdot \frac{T_{sm}-T_{s\infty}}{d} \cdot \frac{d^2}{\mu_F} \cdot \frac{1}{\alpha_F}$
Temperature Number	$\theta \equiv \frac{T_w - T_{sm}}{T_{sm} - T_s}$
Width	$\tilde{d} \equiv \frac{d}{\delta}$
Depth	$\tilde{\Delta} \equiv \frac{d}{\Delta}$
Raleigh Number	$Ra \equiv \frac{gd^3(\rho_F - \rho_{F\infty})}{\rho_{F\infty} \nu_F \alpha_F}$
Second Peclet Number	$Pe2 \equiv \frac{u\,d}{\alpha_F}$
Third Peclet Number	$Pe3 \equiv \frac{\dot{m}'' d}{\rho_g \alpha_g}$

Mass Transfer number $B \equiv \frac{\rho_g C_{pg}(T_{sm}-T_{s\infty})}{L}$

Nondimensional x $\xi \equiv \frac{x}{d}$

Nondimensional y $\eta \equiv \frac{y}{d}$

With these definitions, Eqs. (50), (52), (53), (54) and (57) respectively become the following:

$$Pe1 = Ma \cdot \theta \cdot \tilde{d} \cdot \tilde{\Delta}/2e \qquad (50)$$

$$Pe1 = Ra/2 \qquad (52)$$

$$1/\tilde{\Delta} = Ma \cdot \theta \cdot \tilde{d}/e\ Ra \qquad (53)$$

$$Pe2 = Pe1 \cdot \tilde{\Delta} \qquad (54)$$

$$Pe3 = \theta \cdot B \cdot \tilde{d} \cdot e^{-\xi^2} \qquad (57)$$

The predominant effect of gravity enters into the condensed-phase problem through the Raleigh number. One must, of course, not forget the fact implicit in our over-simplification of the considered gas-phase problem in which the gravitational constant plays no small role. This role is probably buried in the definition of our θ. These identifiable as well as ambiguous roles of gravity require further investigations some of which might benefit immensely by the opportunity of prolonged programmed gravity production in the Spacelab.

CHAPTER C IX

FLAME PROPAGATION OVER LIQUID POOLS THAT ARE INITIALLY ABOVE THEIR FLASH POINT

Introduction:

An unusual character is exhibited by the flames propagating in layered gas mixtures such as those encountered over evaporating fuel pools. The measured propagation speeds are consistently four to five times larger than the fundamental flame speeds of stoichiometric mixtures. The reasons underlying this peculiar enhancement of the flame propagation rate are not fully explored to date. The problem is an important one in fire safety practice since layered gas mixtures are encountered quite frequently. Some example situations include the dispersion of: fuel vapors over an evaporating liquid fuel pool or spill, gaseous fuel emanating from a leak in a pipeline or a tank, methane layers near the ceiling of a coal mine roadway, combustible pyrolysates flowing under the ceiling of a long corridor of a structure inflicted by a fire, etc.

Burgoyne and Roberts [12] studied flame spread over liquid fuels to note the unexpectably high propagation velocities. They attempted to explain their observations on the basis of surface-tension-driven flows in the condensed-phase which enhance the heat feed-forward rate and hence the propagation speed. We will discuss this case in the next chapter.

Phillips [13] investigated flame propagation in methane layers in a model mine gallery in attempts to scale the full scale studies of Meerbach [14] and Perlee [15]. Liebman, Corry and Perlee [16], Feng, Lam, and Glassman [17] and, most recently Kaptein and Hermance [18] and Hirano et al. [19] reported further investigation of the problem of horizontal propagation of flames through vertically diffusing mixtures. These investigations include both analytical and experimental studies. To briefly review these pieces of literature is the objective of this chapter in attempts to find where and how gravitational effects may intrude into the problem and to discover if programmed low-g experiments offer any unique advantage in understanding the problem better.

Scale Dependency:

Maximum flame speeds were obtained by Liebman [16] when the content of fuel was such that upon mixing with the air in the entire gallery, a stoichiometric mixture is obtainable. Whereas the fundamental flame speed of a stoichiometric mixture of methane in air is known to be about 37.3 cm/sec, Liebman measured average flame propagation velocity of about 183 cm/sec. In larger scale galleries, the velocities measured were even higher than this value. Perlee et al [15] employed a 6.5 ft diameter 67 ft long tunnel and measured methane-air flame speeds lying between 213 and 315 cm/sec. Meerbach's [14] 65 ft^2, 198 ft long tunnel yielded speeds in the range of 254-457 cm/sec.

These results lead one to believe that the increased linear scale of the tunnel would increase the flame speed, perhaps due to increased turbulence. If this belief were not farfetched, then it is expectable that gravity has an important role to play both in the generation and suppression of the turbulence. There exist to date no studies to examine this expectation. The correlations presented by Liebman et al [16] involve various physical dimensions of the experimental galleries confirming the possibility of the importance of gravitational body forces. The well-known Richardson number may be employed to account for these gravity effects.

$$Ri = \frac{g(\rho_F-\rho_\infty)h_F}{\rho_\infty(V_1-V_2)^2}$$

g is acceleration due to gravity, ρ_F is the fuel layer density, ρ_∞ is the ambient air density, h_F is the fuel layer thickness and (V_1-V_2) is the relative velocity between the fuel layer and air, this difference being caused by the volumetric expansion due to combustion. Current earth-based practice of obtaining a range of Richardson numbers involves variation of all the variables entering into the preceding definition except the gravity constant. Spacelab experiments will permit the extra degree of freedom through variation of g to realize a broader range of Ri for investigation.

Phillips' [13] flames, like those of Liebman [16], propagating along methane layers indicated that the flame volume depends both on the total quantity of methane present and its distribution in the layer. The flame zone could be divided into three distinct regions: A premixed flame propagating through the 5% to 15% methane mixture, a diffusion flame separating the methane-rich from the air-rich combustion products, and a convection (wake) flame. In the premixed flame, the flame speed was constant except when the radius of the advancing flame front was very small. The role played by gravity on this radius is unclear at present. Gravity is expected to pose a strong influence on both the diffusion and convection flames. In Figure 9 we adapt the Liebman description to depict the anticipated pattern of flame propagation.

Accelerative Behavior:

There has been expressed some speculation that flames propagating in layered gases tend to transit from a slow-moving to an explosive process. Liebman's [16] gallery flames exhibited an accelerative behavior. Theories are postulated by Glassman's group [17] to describe flame propagation through layered fuel/air mixtures. Both the predictions and experiments indicate that for open-ended channels of finite length and finite height, the flames always propagate acceleratingly. The shape of the propagating flame front is speculated

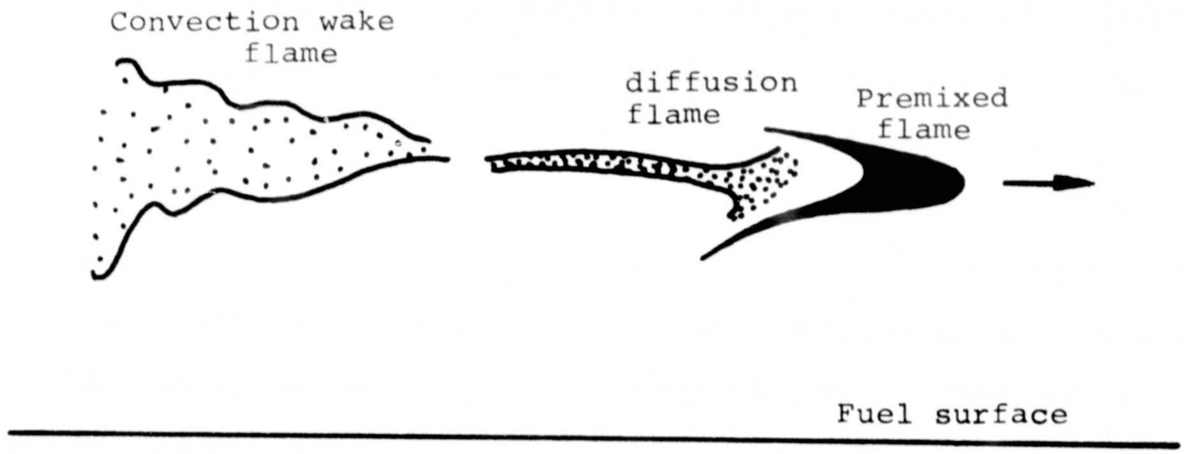

Figure 9 Flame Propagation when the fuel is above its flash point

to influence the propagation rate as well as acceleration. It is expectable that gravity may exert an effect on this shape even though Glassman's theory does not explicitly account for this. Why does the increased propagation speed seem to be explainable on the basis of gas dynamics alone? Why are Feng and Glassman's predictions of propagation in galleries of infinite extent consistently (1.6 times) lower than the observed? Does gravitational effect on the gas mass contained in the burnt and unburnt regions have anything to do with this difference? Kaptein and Hermance [18] recently reported a piece of work concluding that the answer to this last question is in the affirmative. In the absence of the availability of the full paper of reference 18, we can not now go any further. But it is conceivable that if gravity does play a significant role, then the Spacelab experiment ought to enable us to establish this role on firm grounds.

An Unclear Thought:

Hirano and his coworkers [19] reported at the recent Combustion Symposium the influence of concentration gradients normal to the direction of flame propagation over methanol and ethanol liquid fuel trays. They noted that the flame behavior was much different from propagation through a homogeneous mixture. The leading flame front usually precursed through a layer whose composition is near sotichiometric. It is the velocity of this leading flame front that was extensively measured by Hirano. An increase in the concentration gradient (absolute value) in the layer, and an increase in the departure of concentration in the layer from the stoichiometric, both decreased the propagation speed. As the product of the combustion chamber height and the absolute value of concentration gradient is increased the propagation velocity decreased. The precise implications of the variables considered by Hirano and the velocities measured are unclear to us at present. It is also unclear to us how this work fits with the existing other works discussed in this chapter But it is clear that the preponderant issue with Hirano's observations lie in the definition of flammability limits. Strehlow's work [20] in this respect is expected to hold the key explanations.

Remarks:

The problem of flame propagation in a nonuniform composition field over an evaporating pool suggests that gravity has a profound effect on the propagation speed. The current tate-of-the-art is seriously hampered by the lack of an independent explicit control of the gravitational constant. The opportunity afforded by the Spacelab is expected to help in understanding the role of buoyancy in the considered process of enabling measurements over a broader range of conditions than are possible on earth.

CHAPTER C X

FLAME PROPAGATION OVER LIQUID POOLS THAT ARE INITIALLY BELOW THE FLASH POINT

Flame propagation over a horizontal pool of fuel follows one of two possible distinct patterns [21] depending upon whether the fuel's initial temperature is above or below its flash point. When the temperature is above the flash point a combustible mixture exists above the liquid surface. After ignition (which is expected to follow the concepts of Chapter C VII), a flame would then propagate through the combustible mixture in a manner anticipated in the discussions of Chapter C IX. In this propagation process, the gas phase mechanisms of heat and mass transfer exert the control.

When the fuel temperature is below the flash point, however, the propagating flame will have to preheat the fuel ahead of it continuously, this preheating being just adequate to raise the adjacently located fuel element to the flash point. The flame then creeps forward to this heated element and proceeds to heat the next element. Keeping aside the importance of thermal radiation, this preheating can occur by conduction and convection in both gas and liquid phases. The gas-phase heat transfer becomes inconsequential since the gas-phase conductivity is relatively negligible and since the gas-phase convective flows oppose the flame propagation direction. The liquid-phase conduction is smaller by about an order of magnitude [22] than the liquid-phase convection which occurs in the same direction as flame propagation.

Experiments of Roberts [12], and Mackinven [23] showed that the condensed phase flow is induced by the flame itself and the two of the most influential parameters are the liquid viscosity and the sensitivity of liquid surface-tension to the surface temperature. The situation as described by Glassman [22] is as follows.

The surface-tension of most fuels of interest decreases with increasing temperature. Now as one fixes the coordinate system on the flame front spreading over a horizontal fuel bed of a finite depth, the surface temperature decreases rapidly with distance upstream of the flame front, and consequently the surface-tension increases. The variation of surface-tension essentially pulls the surface liquid away from the flame front. Thus hot liquid is carried forward in the direction of the propagation, such convection transporting the heat to prosper the propagation.

Sirignano and Glassman [24] and Torrance [25] carried out theoretical analysis of the flame propagation controlled by surface-tension flow. There are four forces of interest in the problem; these are: inertial, gravitational, viscous and surface-tensional. These four forces result in three independent parameters to describe the problem. For flows driven by surface-tension, the order of magnitude of the velocity is determined by a balance between the surface-tension force and the viscous force at the surface. Thus if h is the fuel layer depth, u is the surface liquid velocity, μ is viscosity, σ is surface-tension and x is the direction of flame propagation and surface flow, then

$$N_1 \equiv \frac{\text{surface-tension force}}{\text{viscous force}} \simeq \frac{d\sigma/dx}{\mu u/h} \simeq 1$$

The ratio of inertial and viscous forces gives Reynolds number

$$Re \equiv \frac{\text{inertial force}}{\text{viscous force}} \simeq \frac{\rho u^2}{\mu u/h} = \frac{\rho u h}{\mu}$$

The ratio of gravitational force to the inertial force results in the Froude number.

$$Fr \equiv \frac{\text{buoyancy force}}{\text{inertial force}} \simeq \frac{\rho g h}{\rho u^2} = \frac{g h}{u^2}$$

It is customary to use Grashof number instead of Froude number in most heat transfer problems by noting that $GR \equiv Fr \cdot Re^2$.

$$Gr \equiv \frac{\text{buoyancy force . inertial force}}{\text{viscous force}^2} \simeq \frac{gh^3\rho^2}{\mu^2}$$

The importance of other sophisticated forms of Grashof number, ex: Raleigh number, does not need special stress here. But it seems instructive to resolve $N_1 = 1$ into the velocity $u \approx [h\, d\sigma/dx]/\mu$ and substituting this into the Peclet ratio of surface tension induced convective heat transfer to the conductive heat transfer. The result is what is known as Marangoni number, Ma.

$$Ma \equiv \frac{\rho C_p hu}{K} = \frac{\rho C_p h}{K} \frac{hd\sigma/dx}{\mu} = \frac{\rho C_p h^2}{\mu K} \frac{d\sigma}{dT} \frac{dT}{dx}$$

Torrance [25] computed the flame spread Reynolds number as a function of Marangoni and Grashof numbers. His main finding was that buoyancy and surface-tension work hand-in-hand to produce a thermal convection cell which enables the flame to propagate forward. The effect of buoyancy is small and nearly indistinguishable for $Gr \approx 10^4$. At Grashof number of about 10^6, buoyancy appears to influence the flows about as much as surface-tension. In contrast to this, Glassman [24] assumes gravity's influence is realized through hydrostatic pressure which opposes the surface-tension-driven flow. Under these circumstances the absence of gravity would significantly affect the flame spread rate.

It is clear that there is not a firm understanding of the role gravity plays in flame spreading processes. Carefully conducted experiments in reduced gravity offers the prospect of shedding light on these complex phenomena.

CHAPTER C XI

FULLY DEVELOPED POOL BURNING IN A QUIESCENT ENVIRONMENT

Small Pools:

Some peculiarities are exhibited by the combustion of liquid pools whose diameters are small, say less than 2 cm. Both the flame height and the evaporation rate are usually much larger than those expectable from natural convection heat transfer considerations. An increase in pool diameter is known to rapidly decrease both the flame height and burning rate.

The reason for these pecularities may be best seen by recalling that the flame under consideration is like a hollow vertical tube sitting on the pool as its base. The inside of this tube is filled essentially with the fuel vapor. Most of the heat feedback from the flame to the fuel surface is then expected to occur from the lower circular rim of the flame mainly due to gas-phase conduction. Convection and radiation from the tube of the flame are expected to be inconsequentially small. If the pool were to be held in a pan, the flame may deliver heat to the pool through the edge of the pan, a deduction drawn from the observed influence of the pan material on the vaporization rate and the flame size.

If T_f is the flame temperature and T_W is the temperature of the fuel surface (or of the metallic pan rim), the heat feedback flux is given by $\dot{q}'' \simeq K_g (T_f - T_W)/\delta$ (cal/cm^2 sec). Hence δ is the effective distance between the lower circular rim of the flame tube and the fuel surface (or pan rim). It is in some respects similar, or related, to the classical quenching distance. Let h'be the free-board height; it is the distance (vertical) between the upper edge of the pan and the surface of the fuel contained in the pan. h', of course, will increase with time as the fuel is consumed. Then the total heat transfer to the fuel is given by $\dot{q} = \dot{q}'' \pi d h'$ where πd is the periphery which gives the area of heat transfer when multiplied by h'. The average mass transfer rate $\dot{m}''$ is then given by $\dot{m}'' \simeq \dot{q}/(\pi d^2 L/4)$ where L is the latent heat of vaporization. Thus,

$$\dot{m}'' \simeq \frac{K_g(T_f - T_W)}{\delta} \cdot \frac{\pi d h'}{\pi d^2/4} \cdot \frac{1}{L} \tag{58}$$

Noting that h' increases with time of burning at a rate $\dot{m}''/\rho_F$ where ρ_F is fuel density, Eq. (58) may be integrated to obtain

$$\dot{m}'' \simeq \frac{4K_g(T_f - T_W)}{Ld} \cdot \frac{h'_o}{\delta} \cdot \exp\left[\frac{4K_g(T_f - T_W)t}{\rho_F \ \delta L d}\right]$$

Here t is time and h'_o is the initial free board height.

In the absence of a pan holding the fuel, (say, burning of a polymer rod), h is replaced by the flame thickness (which is known to be of the same order as the quenching thickness δ) in the expression for the area of heat transfer Thus $\dot{q} \simeq \dot{q}''\pi\delta d$ so that

$$\dot{m}'' \simeq \frac{K_g(T_f - T_W)}{\delta} \quad \frac{\pi d \delta}{\pi d^2/4} \cdot \frac{1}{L}$$

The location of the flame base relative to the regressing fuel surface will then be constant and the consequent mass transfer rate is independent of time.

$$\dot{m}'' \simeq \frac{4K_g(T_f - T_W)}{dL}$$

In both the cases discussed above, $\dot{m}'' \propto d^{-1}$. In the case when the fuel is contained in a pan, the sensitivity of m'' to time t is accentuated by a decrease in pan diameter. Even more important, however, is the expected strong dependency of δ on gravity. The existing literature deals with this problem no more quantitatively than the description given above.

Intermediate-Size Pools:

If the pool diameter is between 2 and 8 cm, the predominant heat feedback mechanism is free convection. In this domain, the burning rate decreases with increasing diameter relatively less rapidly than in conductive domain; i.e., $m'' \propto d^{-n}$ where n lies between 1/4 and 1/2. This dependency may be explained by the following mechanism.

Considered as a purely free convective process, the Nusselt number associated with heat transfer to the fuel from the flame, hd/K_g is known [5,26] to be proportional to the Grashof number $(gd^3\ \beta\Delta T/\nu_g^2)$ raised to a quarter power. The heat transfer coefficient h heat flux and hence mass transfer rate, then, are proportional to inverse quarter power of the pool diameter.

$$\dot{m}'' \simeq C_1 K_g (T_f - T_W)(g\beta\Delta T/\nu_g{}^2)^{1/4}/Ld^{1/4} \tag{59}$$

On the other hand, the process may be considered as a forced convective heat transfer in which the flow is caused by the buoyant plume at a velocity U proportional to $(g\alpha_g\beta\Delta T)^{1/3}$ cm/sec. The flat plate laminar heat transfer then is given by $hd/K_g = C_2\ (Ud/\nu_g)^{1/2}$ so that $h \propto d^{-1/2}$, and

$$\dot{m}'' \simeq C_2 K_g (T_f - T_W)\ [C_3 (g\alpha_g\beta\Delta T)^{1/3}/\nu_g]^{1/2}/Ld^{1/2} \tag{60}$$

where C_2 and C_3, like C_1, are constants of proportionality.

At the suggestion of Professor Eckert, Blackshear and Kanury [5] considered the pool flow as similar to the flow behind a bluff body; this assumption, too, invokes a Nusselt number proportional to the Reynolds number raised to half-power, thus leading to the conclusion $\dot{m}'' \propto d^{-1/2}$ by an alternative argument.

Large Pools:

For pool diameters larger than 8 to 10 cm (which includes the sizes of our present concern), the flow transits from laminar to turbulent. Fully developed turbulent flow may be expected for $d>10$ cm. The Nusselt number then is known to be proportional to the cube root of the Grashof number so that

$$\dot{m}'' \simeq C_4 K_g (T_f - T_W)(g\beta\Delta T/\nu_g^{\,2})^{1/3}/Ld^o \tag{61}$$

in complete agreement with the observations, i.e., m'' independent of d for nonradiating fires [5,26,28].

Larger Pools:

For pools of size $20<d<100$ cm, the fire may be fully turbulent and yet not necessarily follow Eq. (4) due to the effects of radiation. In this domain, the emissivity of the flames is known [5] to increase according to

$$\varepsilon' \simeq 1 - \exp(\kappa'\ell) \tag{62}$$

where κ' is the absorption coefficient known to be proportional to the soot concentration in the flames and ℓ is the radiation path length in the flames. Radiation literature [28] indicates that $\ell \simeq 4V_f/A_f$, where V_f and A_f, respectively, are the flame volume and surface area, their ratio being proportional to the flame height H_f. A dimensional comparison of the time taken by the fuel to reach the tip of the flame and the time taken to mix air turbulently across the cross section of the flame leads to the relation $H_f/d \propto \dot{m}''d/\rho_F\varepsilon$, where ε is the eddy diffusivity. Since the mixing length is of the order of the pool diameter and the velocity of relevance is of the order of $\dot{m}''/\rho_F$, it is to be expected that H_f/d is a constant, a matter confirmed [29] experimentally to be true. This constant is about 1.5. Hence Eq. [62] may be rewritten as

$$\varepsilon' \simeq 1-\exp\,(C_5[\text{soot}]d)$$

For nonluminous flames, the soot concentration $[\text{soot}] \simeq 0$ so that $\varepsilon' \simeq 0$. Only band radiation effects then come into the picture. For luminous sooty combustion, on the other hand, ε' increases with pool size slowly to assymptotically reach $\varepsilon' \to 1$ when d is large. Thus the large radiative turbulent pool combustion rate may be estimated as

$$\dot{m}'' \simeq \left[C_4 K_g (T_f - T_W)(g\beta\Delta T/\nu_g^2)^{1/3} + \sigma'\varepsilon'(T_f^4 - T_W^4)\right]/L \qquad (63)$$

where σ' is the Stefan-Boltzman constant.

Equation (63) explains the slowly increasing dependency $\dot{m}''(d)$ noted in various experiments on pools with diameter between 20 to 100 cm. Beyond this upper limit, the flames become thick in an optical sense, ε' becomes unity, and the burning rate becomes independent of pool size. Under these fully "developed" radiation and turbulence conditions, the ratio of radiative heat loss rate to the combustive heat generation rate is obtained from Eq. (63) as

$$\frac{\dot{q}_{rad}}{\dot{m}\Delta H} = \frac{L\sigma'(T_f^4 - T_\infty^4)/\Delta H}{C_4 K_g (T_f - T_W)(g\beta\Delta T/\nu_g^2)^{1/3} + \sigma'(T_f^4 - T_W^4)} \qquad (64)$$

This function is in fact independent of the pool size and depends only on the nature of the fuel and "free stream."

Some Deductions:

The most common feature shared by observations on pool fires of a hundred feet or so in diameter is that black billowing clouds of smoke are produced, perhaps due to the drastic inadequacy of mixing. The same inefficient mixing leads to the suspicion that perhaps a cloud of unburnt fuel vapor exists above the central region of the pool, attenuating the radiative feedback. So much as this cloud will be larger for larger pools, one might expect that the average burning rate of these large pools decreases weakly with increasing pool size. In reality, however, such a decrease is not exhibited by large pool fires, and, if truly present, is apparently overwhelmed by the intense constant turbulent convective heat flux.

In the entire steady state burning of fuel pools, gravity is expected to come into play in determining the flame location and shape; that is, in determining δ or consequently the heat transfer coefficient h. When the pools are of considerable size, gravity is also expected to play a role in deciding the residence time of radiating soot particles in the high temperature regions. This latter effect is important not only in obtaining the burning rate as influenced by radiative feedback, but also in discerning observations on flames by visual or photographic techniques.

CHAPTER C XII

FLAME SIZE AND SHAPE

The flame shape and size are crucial in several ways. First, the shape of the flame becomes helpful in deducing an approximation to the conductive heat-feedback to the fuel surface. Second, it gives a basis to pass judgments on the flame behavior from visual and photographic observations. Third, the flame shape, volume and surface area are variables of basic interest in assessing the radiant heat power of the flames both toward the evaporating fuel surface and toward the ambience at large.

In the simplest spirit, the height ℓ of a diffusion flame fed with fuel at a volumetric rate of $\dot{V}_F$ cm^3/sec through a source of diameter d is given by the relation [30]

$$\frac{\ell}{d} = a_1 \left[\frac{\dot{V}_F^2}{gd^5}\right]^b \tag{65}$$

where g is the acceleration due to gravity and a_1, b are constants. The bracketted term is a form of the Froude number. According to Putnam and Speich [31] the coefficient a_1 is about 30, and according to Thomas [32] the exponent b lies between 1/5 and 1/3. The volumetric flow rate is given by the mass flow rate per unit area $\dot{m}''_F$, the density of gases near the fuel surface ρ_{Fs} and the area of vaporization $\pi d^2/4$.

$$\dot{V}_F = \frac{\dot{m}''_F}{\rho_{Fs}} \frac{\pi d^2}{4}$$

so that Eq. (65) becomes

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$$\frac{\ell}{d} = a_1 \left(\frac{\pi}{4}\right)^{2b} \left[\frac{\dot{m}''^2_F}{\rho_{Fs}^2 gd}\right]^b \tag{66}$$

If one assumes that the flame is conical in shape, with base d and height ℓ, the surface area A of the flame through which air is entrained and the volume V covered by the flame cone are:

$$A = \frac{\pi d^2}{4} \left[1 + \left(\frac{2\ell}{d}\right)^2\right]^{1/2} \tag{67}$$

$$V = \frac{\pi d^3}{12} \frac{\ell}{d} \tag{68}$$

According to these relations, a decrease in g increases the flame size, rather drastically. As g tends to zero in the limiting case, the length (as well as area and volume) tend to infinity; this behavior violently contradicts our intuition; and it is clear that the basic mechanisms of transport might themselves be different under these severe limit conditions. The solution to this dilemma might lie in the following argument.

The volumetric flow rate of air $\dot{V}_a$ induced into the combustion cone is equal to the product of the velocity of entrainment and the area of the conical surface. The entrainment velocity is proportional to $(g\ell)^{1/2}$ so that

$$\dot{V}_a = a_2 \, (gd)^{1/2} \left(\frac{\ell}{d}\right)^{1/2} \frac{\pi d^2}{4} \left[1 + \left(\frac{2\ell}{d}\right)^2\right]^{1/2} \tag{69}$$

Knowing the ℓ/d dependency on gravity, this equation shows that the entrainment rate is proportional to g-raised to a power of about 1/3. Thus as $g \to 0$, $\dot{V}_a \to 0$ and the combustion itself is expected to cease to occur according to the convective-diffusive mechanism implicit in Eqs. (65) to (69).

The same conclusion could also be arrived from a different view point. If the pool were to evaporate as a result of free convective heat transfer, the mass transfer rate is given roughly by

$$\dot{m}''_F = \frac{h(T_f - T_s)}{L} \tag{70}$$

where L is latent heat, and the heat transfer coefficient h is given by $h \propto g^{1/4 \text{ to } 1/2}$. Thus as $g \to 0$, $\dot{m}''_F$ itself tends to zero. The precise deduction of these g-dependencies require a more scrupulous analysis than the present one; but suffice it to say that there exist a series of ambiguities which need to be pinned down to understand better the shape and size of flames under variant gravity conditions.

CHAPTER C XIII

EXTINGUISHMENT

Introduction:

The conditions surrounding the inability of a flame to self-perpetuate, or the impossibility of initiating the flame itself in the first place are of critical interest in at least three respects: (a) in designing the Spacelab experiment for successful achievement of ignition; (b) in understanding the competition of physical and chemical processes culminating in extinguishment phenonenon; and (c) in delineating the thresholds of nonexistence of our hypothetical microfire (to be discussed in next chapter).

A study of the extinguishment process may be done either by scrutinizing the energy and material balances (or imbalances) in a flame and identifying the critical conditions under which the flame squelches itself; or by delineating the conditions which are not conducive to the existence of the flame, i.e., the limits of ignitibility. In both these view-points the factors which need reckoning include all those influencing the generation and dissipation of heat as well as any crucial active chemical species. A partial list may be prepared mentioning: the thermal conductivity of both the gas and liquid phases; volumetric heat capacities; flow and geometric parameters including gravity; thermodynamic properties such as heats of combustion and vaporization, and as the ambient temperature, equilibrium surface temperature, etc; thermochemical properties such as the overall stoichiometric ratio; parameters entering into the kinetics of combustion reaction mechanisms; and others.

No thorough analyses or experiments are available to date to synthesize the whole picture of extinguishment and to separate the numerous variables into groups. There exists the unique possibility that a thoughtful dimensional analysis will reveal the mechanisms involved in the problem and will offer a scrupulous method of varying one or more nondimensional numbers via variations in gravity available in the Spacelab facilities.

A Preliminary Theory of Extinguishment:

Viewing extinguishment as a result of the inbalance between the rates of heat generation and dissipation and simplifying that the chemical reactions may be expressed by an overall n-th order rate equation, we can postulate a simple thermal theory of extinguishment [30]. The criterion for extinguishment employed in this theory is that if an already existent flame were to be inflicted by extinguishment conditions, then the temperature T of the reaction zone falls with time t and falls rapidly.

Denoting the flame volume and surface area respectively by V and S, volumetric heat capacity of flame gases by ρC, effective conductivity by K, heat generation rate by $\dot{q}_g'''$ and surface-normal unit vector by $\overline{n}$, the flame energy balance is expressed by

$$\frac{\partial}{\partial t}\int_V \rho CT \, dV = \int_S K \frac{\partial T}{\partial n} \, dS + \int_V \dot{q}_g''' \, dV \tag{71}$$

That at extinction the flame-gas enthalpy decreases with time implies that the $\partial/\partial t$ term of Eq. (71) (and hence the right hand side) is either negative or zero. That this decrease is rapid is expressed mathematically by a negative (or zero) time-derivative of either side of Eq. (71). At the critical extinguishment conditions, these two derivatives are equal to zero. Denoting the heat generation as a simple Arrhenius expression,

$$\dot{q}_g''' = \Delta HV \, k \, \rho^n Y_O^m Y_F^{n-m} \exp(-E/RT) \tag{72}$$

where ΔH is heat of combustion, k is preexponential factor, ρ is density, Y_i is mass fraction of species i(i: O for oxygen and F for fuel), E/R is activation temperature, and n and m are orders of reaction. Now employing the flame area and volume relations of the last chapter, the extinguishment condition is stipulated [30] by

$$\left[\frac{E}{RT_g}\right]\left[\frac{1}{Y_{o\infty}}\right]\left[\frac{\rho_\infty(gd)^{1/2}C(\pi d^2/4)(E/R)}{\Delta Hk\rho_s^n(\pi d^3/12)}\right]^{1/m}\left[\frac{\rho_s(gd)^{1/2}L}{hE/R}\right]^{\frac{(n-m)(1-3b)-b}{m}} = \text{const.} \quad (73)$$

The subscripts ∞ and s as usual refer respectively to the ambience and fuel surface. h is the feedback heat transfer coefficient and L is the lateat heat of vaporization. b is the flame height index discussed previously.

Each of the square-bracketted terms in Eq. (73) is a nondimensional number. The first of these in which gravity appears is a ratio of a free convective gas heating rate to a representative combustion heat release rate. Thus this is a sort of Damkohler number. The second nondimensional quantity involving gravity is a ratio of two heat fluxes; the numerator is a measure of the heat flux demand by vaporization and the denominator is a measure of the heat feedback flux.

<u>Discussion:</u>

Taking for a first approximation $n \simeq 2$, $m \simeq 1$ and $b \simeq 1/5$, Eq. (73) leads to the following observations on the critical conditions of extinguishment.

(1) Ambient Pressure affects not only the feedback heat transfer ($h \propto P^{1/2}$ in laminar free convection) but also the reaction rate coefficient $k\rho_s^n$. Eqaution (73) shows that the flame is more difficult to extinguish at higher pressures, keeping everything else constant. Note, however, that the increased collisions may reduce k if the collisions occur among active free radicals. Then the influence of pressure on h and ρ_s opposes its own influence on k and then the implications of varying the pressure are unclear until the precise reaction mechanisms are known.

(2) This model predicts that flames on larger pools are harder to extinguish. Even though an increase in the sixe of the pool is expected to bring about an increased flow to dissipate the heat, such an increase is

greatly overwhelmed by the increase in the flame volume in which the heat is generated.

(3) Finally, quite importantly, the extinguishability, (which is perhaps defined as the inverse of the oxygen mass fraction at which extinguishment occurs), is inversely proportional to $g^{0.6}$. As the gravitational acceleration is reduced, the flame resists extinguishment even at lower oxygen concentrations. The reason, according to our theory, is that decreased g-values lead to increased effective flame lengths (and hence, greatly increased reaction volume to loss surface ratio). Furthermore, the entrainment velocity of ambient air is directly proportional to the square root of g. This again results in reducing available oxygen to sustain a flammable mixture in the combustion zone. There exist no data what-so-ever to substantiate or denounce these predictions. Experiments in the Spacelab provide well-defined g-values for long enough time to obtain the necessary data which are crucial not only to learn more about effective fire safety in spacecrafts but also to develop a clear understanding of the phenomenon of extinguishment itself.

CHAPTER C XIV

MICROFIRE

What is a 'Microfire'?

The concept of 'microfires' is intrinsically interesting enough to seek for ways of producing them. One method of arriving at a microfire in earth-based laboratories is simply to consider combustion of minute particles of a fuel whose diameter approaches zero. These experiments on vanishingly small bodies, however, do not permit a detailed probe measurements of the characteristics of combustion and flame. Add to this, the complication of vanishingly short life time of these particles, the problem becomes impossible.

The gravitational control of microfire behavior manifests [10] through the Grashof number

$$Gr \equiv \frac{\Delta\rho}{\rho} \frac{g\ell^3\rho^2}{\mu^2}$$

where $\Delta\rho$ is the characteristic density difference in gas-phase which causes gravitational body forces, ρ is gas-phase density, g is gravitational constant, ℓ is the characteristic linear dimension of the body and μ is dynamic viscosity of the gas-phase. A gradual reduction in Grashof number can be brought about not only by gradually reducing the characteristic dimension ℓ but also by reducing the gravitational constant g and ambient pressure (and hence density ρ).

Methods [33,34] have been developed to study large fires burning at atmospheric pressure by conducting small scale model experiments burning at elevated ambient pressures. Fully turbulent convective mechanisms may be reproduced, if the scale, gravity and pressure are so chosen between the model and prototype fires as to preserve the Grashof number invariancy.

In the limit $g \to 0$, a situation of $Gr \to 0$ is approached. In this limit, the only mass transfer mechanism feasible is diffusion* and the properties of the system are independent of the scale, orientation, and geometry. A new concept termed here "Microfires", thus, evolves. Thus, it is suggested that physically large (ℓ) fires at low gravity level and in low pressure atmosphere will model what are small scale phenomenon on earth so long as the product $g\ell^3P^2$, and hence Gr, is kept invariant. The microfire characteristics are fundamental properties of the material being burnt, and essentially independent of the convective processes. Knowledge in this respect is deemed to be of immense practical utility in better designing our power plants which employ pulverized coal and liquid fuel sprays. Taking advantage of achieving various low gravity levels in space, can we scale 'up' combustion of bodies, of size conveniently amenable for probing, in order to study processes that are inaccessible on earth because of size and time constraints? The answer for this question comes only from actually trying to generate this hypothetical fire. We present, in the following, a preliminary modeling scheme for microfires.

A Modeling Scheme:

Gravitational controlled combustion phenomena involve the following three nondimensional numbers.

Grashof $$Gr \equiv \frac{\Delta\rho}{\rho} \frac{g\ell^3\rho^2}{\mu^2}$$

Froude $$Fr^{-1} \equiv \frac{\Delta\rho}{\rho} \frac{g\ell}{u^2}$$

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*Dodge et al. [35] argue that even though normal flows induced by buoyancy are nearly absent at very low gravity levels (i.e., $g<10^{-3}$ cm/sec^2), the flows generated by nongravity forces will continue to prevail and to become significant. Such nongravity forces may result from surface or interfacial tensions, thermal-volume expansions, density changes caused by phase change, magnetic and electric fields, etc.

Reynolds $\quad Re \equiv \frac{\rho u \ell}{\mu}$

u is the externally controlled flow velocity. It is clear that $Gr = Fr^{-1} \cdot Re^2$. Let subscripts m and e respectively refer to the micro and earth-based fires. Note that by gas law, $\rho = P/RT$. Let unsubscripted quantities refer to gas-phase whereas quantities subscripted by c refer to the condensed-phase. Assuming that the dynamic viscosity μ and flame temperature T_f (and hence the ratio of density differential to density $\Delta\rho/\rho$) are independent of both the gravity g and gas pressure P, then Gr is kept invariant if

$$g_m \ell_m^3 P_m^2 = g_e \ell_e^3 P_e^2$$

The earth based fire is the real fire so that $g_e = 1$ and P_e = the furnace pressure. Let

$$g_m/g_e \equiv b \qquad\qquad P_m/P_e \equiv a$$

The invariance of Grashof number leads to the following prescriptions.

1. Lengths:

$$\ell_m/\ell_e = b^{-1/3} \quad a^{-2/3} \tag{74}$$

2. External Velocities:

Under the scale reduction rule of Eq. (74) to preserve the forced convective processes, Reynolds number has to be kept invariant. This is done by keeping $uP\ell$ = constant so that

$$u_m/u_e \equiv b^{1/3} \; a^{-1/3} \tag{75}$$

Note that the scale-velocity-prescription of Eqs. (74) and (75) automatically keep the Froude number invariant.

3. Gas-Phase Characteristic Time:

The Fourier number $Fo \equiv \alpha t/\ell^2$ where α is thermal diffusivity

(= conductivity/volumetric heat capacity). Prandtl number $Pr \equiv \nu/\alpha$ where ν is kinematic viscosity ($= \mu/\rho$).

$$Fo \equiv t\mu/Pr\rho\ell^2$$

The gas-phase time t is related to the gas flow times or diffusive times. To preserve Fo,

$$t_m/P_m\ell_m^2 = t_e/P_e\ell_e^2$$

so that

$$t_m/t_e = b^{-2/3}a^{-1/3} \tag{76}$$

This result could also have been obtained by considering that $t = \ell/u$. From Eq. (74) and (75) then Eq. (76) follows.

4. Solid-Phase Characteristic Times:

$$Fo_c \equiv \alpha_c t_c/\ell^2$$

so that

$$t_{cm}/t_{ce} = b^{-2/3}a^{-4/3} \tag{77}$$

5. Interface Convective Heat Fluxes:

Nusselt number is $Nu \equiv h\ell/K = f$ (Gr, Re, Fr, Pr) where h is heat transfer coefficient and K is gas thermal conductivity. Note that C_p, μ, K and hence $Pr \equiv \mu/\alpha = \mu C_p/K$ are independent of both g and P if P is not close to the critical pressure. Then

$$h_m\ell_m = h_e\ell_e$$

so that the heat fluxes follow

$$\dot{q}''_m/\dot{q}''_e = b^{1/3}a^{2/3} \tag{78}$$

6. Interface Mass Fluxes

If the effective "latent heats" of fusion and vaporization Q are independent of g and P then $\dot{q}'' = \dot{m}''Q$ so that from Eq. (78)

$$\dot{m}''_m/\dot{m}''_e = b^{1/3}\, a^{2/3} \tag{79}$$

If radiation were to come into the picture Eq. (79) may not hold. However, our pressure-modeling experience suggests that while radiation is not negligible, it is proportional to the convectively controlled burning rates. Why this is so, we do not know at present. Equation (79) remains valid in this case of $\dot{q}''_{rad} \propto \dot{m}''$. Equation (79) could also have been obtained by considering the mass flux $\dot{m}''$ as (ρv) at the interface. Then $\dot{m}'' = (\rho v) \propto Pu$; $\dot{m}''_m/\dot{m}''_e = P_m u_m/P_e u_e$. From Equation (75), therefore, $\dot{m}''_m/\dot{m}''_e = b^{1/3}\, a^{2/3}$. There is yet a third method of deducing Eq. (79). Since $\dot{m}'' \propto m_c/t_c\, \ell^2$ and since $m_c \propto \ell^3$, $\dot{m}'' \propto \ell/t_c$ so that from Eqs. (74) and (77) Eq. (79) results.

7. Thick Fuel Fed Fire Spread Rate:

The fire spread rate V is the ratio of distance between two homologous points and the corresponding solid phase times. $V = \ell/t_c$. From Eqs. (74) and (77), therefore,

$$V_m/V_e = b^{1/3}\, a^{2/3} \tag{80}$$

Equation (80) could also have been deduced from the invariance of the solid phase Fourier numbers $Fo_c \equiv \alpha_c t_c/\ell^2$. Then the velocities ℓ/t_c are related by $V_m/V_e = \ell_m t_{ce}/\ell_e t_{cm}$ which from Eq. (74) leads to Eq. (77). The pressure dependence of spread rate predicted purely on the basis of dimensional analysis arguments here is thoroughly tested by the experiments available in the literature. No data however, are available to test the gravity effects.

8. Thin Fuel Bed Fire Spread Rate:

With the same arguments as in item (7), keeping the solid phase Fourier number invariant,

$$V_m\, \ell_m = V_e\, \ell_e$$

Now realizing that the thickness of the thin sheet τ, for geometrical similarity, is proportional to ℓ,

$$V_m \tau_m / V_e \tau_e = \text{const.} \tag{81}$$

The available experiments validate Eq. (81) so far as the pressure effects are concerned. Further analysis of this thin-fuel spread problem and experimental study of the influence of gravity on the constant in Eq. (81) are required.

9. Volumetric Sources of Heat and Mass of Species i:

These may be considered as flux/unit length so that

$$\dot{q}''' \propto \dot{q}''/\ell$$

Hence from Eqs. (78) and (74),

$$\dot{q}'''_m / \dot{q}'''_e = b^{2/3}\ a^{4/3} \tag{82}$$

The mass sources are proportional to the heat sources, $\dot{q}''' = \Delta H_c \dot{m}_i'''$. Hence from Eq. (82)

$$\dot{m}'''_{im} / \dot{m}'''_{ie} = b^{2/3}\ a^{4/3} \tag{83}$$

Equation (83) may even have been obtained by considering the mass source either as $\rho \partial Y_i / \partial t \propto P/t$ or as $(\rho D)\ \partial^2 Y_i / \partial y^2 \propto 1/\ell^2$ since (ρD) is nearly independent of g and P, Eq. (3) or Eq. (1) leads then to Eq. (83).

10. Reaction Kinetics:

One of the limitations of this modeling lies in the reaction kinetics. When reaction rates are low and the fires cease to be described accurately by diffusion and flow control, some complications may arise. If the overall reaction rate is such that its overall order is 4/3, however, according to Eq. (83) no headaches arise. Gravity experiments are expected to shed important light in this respect.

Summary of Modeling Hypothesis

Here we briefly list all the relations prescribed and derived above for a quick reference.

P_m/P_e	$\equiv a, \quad g_m/g_e \equiv b$	Prescriptions
ℓ_m/ℓ_e	$= a^{-2/3}\, b^{-1/3}$	Scale
u_m/u_e	$= a^{-1/3}\, b^{1/3}$	External velocities
t_m/t_e	$= a^{-1/3}\, b^{-2/3}$	Gas- phase times
t_{cm}/t_{ce}	$= a^{-4/3}\, b^{-2/3}$	Solid-phase times
$\dot{q}''_m/\dot{q}''_e$	$= a^{2/3}\, b^{1/3}$	Interfacial heat fluxes
V_m/V_e	$= a^{2/3}\, b^{1/3}$	Thick fuel fire spread
$\dot{q}'''_m/\dot{q}'''_e$	$= a^{4/3}\, b^{2/3}$	Heat sources
$\dot{m}'''_{im}/\dot{m}'''_{ie}$	$= a^{4/3}\, b^{2/3}$	Species i sources

We can see immediately that with a 6" fire at 0.1 atm. and 0.01 g, we can simulate a 0.25" fire at 1 atm and 1 g. This capability is adequate to model most of the particle fires of interest in combustion.

Something Unknown:

As one proceeds to consider progressively smaller fires which approach the limiting conceptual microfire, one will ultimately arrive at a predominately diffusion-controlled combustion process. Under these circumstances, the supply of reactants to, and the removal of heat and products from, the reaction zone will be considerably feebler by diffusional mechanisms unaugmented by the usual free or forced convection. These feeble diffusional fluxes of mass and heat are expected to culminate in flames which are truely, and ideally, physically controlled. But if the fluxes are so low as to allow occurrence of a phenomenon akin to the classical 'flash-back', the very concept of the ideal microfire falls apart.

Conversely, when one progressively increases the physical rates of supply and removal of the participant chemical species and heat, extinguishment is known to result due to the incapability of chemical kinetics to cope with the excessive physical rates. Conventionally, this sort of a process is used in combustion to study the kinetics from the 'blow-off' data [10].

The dilemma then is this: proceeding in the direction of progressively reduced transport rates, does one encounter a situation where these rates are so low that the relatively infinitely fast chemical kinetics become dissatified with the meager supply rates which are not worth contending with? If so, what do we call the resultant ceasure of the combustion? Is it still an entinguishment? At what threshold combination of physical and chemical conditions does this occur? How does gravity as a promoter of convective transport come into this threshold?

No conclusive answers could now be found to this mosaic of questions. Attempts to produce and characterize microfires, and to locate the threshold of their nonexistence via Spacelab experiments seem to merit consideration.

D. ANALYTICAL JUSTIFICATION

General Comments:

An examination of physics of pool burning indicates the potential need in numerous areas of pool burning phenomena for valuable experimentation in Space. In this summary section, the objective is to discuss this need in some specific depth to point out the scientific and practical value of Space experimentation on burning of liquid fuel pools and the possible benefits that could be realized to technology as a whole.

Study of various facets of the pool burning problem holds the distinction in that a great deal of useful information, both basic and applied, may be obtained. The basic information comes from an advanced understanding of the various interacting forces which often culminate in some unusual and curious behaviors. The applied information comes from seeking for ways of utilizing the improved understanding to different physico-chemical processing methods of interest and promise in enriching the standard-of-life in a technological society.

The fact that a combustion problem is under study becomes even more strikingly impressive since concepts related to combustion and flame traditionally exert a profound influence on the progress in engineering science and chemical reaction chemistry as well as exhibiting a short time constant of incubation before being applied to practical systems.

As a pool of finite depth is set up for the experimentation under varying low gravity conditions in a strategically prechosen gas-phase atmosphere, one can focus attention on one aspect or another of the fluid motion, both in the liquid-phase and the gas-phase. These aspects, evident from the choice of topics for the various chapters of Section C may deal with the preignition, transignition and postignition processes. These three classes of processes and the role played by gravity in them will be discussed later in the present section.

The discussions of Section C in general point out the manner in which various forces (i.e., inertial, viscous, surface-tensional, gravitational, etc.) and fluxes conspire to conserve heat, mass and momentum both in the condensed-phase and gas-phase fields. While some of the theoretical models presented in Chapters C I-C XIV are relatively complete, others are obviously in primitive stages of development. Notwithstanding this partially postulated nature of some of the problems, the discussions lead us to draw several important deductions on the state-of-the-art.

First, most of the processes considered here, or conceivable ever, involve transient effects. Quite frequently, gravity becomes the controlling factor in determining the characteristic time scales. Second, body forces usually invoke three-dimensional effects which are difficult to study analytically as well as experimentally. (This matter becomes even more serious when one attempts experimentally to adapt a problem to two-dimensions; feasibility of the experiment under reduced gravity conditions may thus be severely impaired.) Third, in order to arrive at any solutions, no matter analytical or numerical, a host of assumptions are usually required. While some of the assumptions render the problem tractable, others merely attempt to account for scientific aspects of Nature which are not fully understood. Fourth, quite often crucial input data are unavailable in the existing literature. The dearth of information is especially serious in such topics as chemical kinetics of combustion reactions. Other deductions may also be made from Section C. Suffice it to say that pool burning experiments under reduced gravity conditions bear the potential of filling the gaps of knowledge evident from these deductions.

The prolonged low-gravity conditions which are available in the Spacelab program intensify this promise, thus leading us to arrive at a strong analytical justification for proposing to conduct pool combustion experiments in Space.

In the following, we discuss several issues specifically in which gravity plays a role, and thereby the Spacelab provides an essential and cost-effective environment for their study.

Preignition Processes:

These are discussed in Chapters C I- C VI

Chapter C I: Condensed-Phase Processes in Preignition Evaporation (Case 1: Surface-Tension Flows Unsuppressed);

C II: Condensed-Phase Processes in Preignition Evaportion (Case 2: Surface-Tension Flows Suppressed);

C III: Heat Transfer in the Condensed-Phase;

C IV: Pool Evaporation;

C V: Transient Dispersion of Fuel Vapors into the Quiescent Atmosphere; and

C VI: Formation of Combustible Space in the Gase-Phase.

Concerned with certain curious motions observable at the surfaces of wine and other alcoholic beverages, and at the surface of a tub of soapy water, scientists discovered a hundred years or so ago the competitive nature of surface-tension forces with body forces of gravity. These observations are of interest in a wide range of practical applications. On a large scale, the unstable flow of liquids and their mixing are relevant in prediction and management of aquatic life and pollutant sedimentation in lakes and rivers. The same considerations will also be useful in the prediction of freezing of lakes and rivers. On a moderate scale, design of many multiphase contact devices of chemical process industry (i.e., distillation, absorption, separation and extraction units) calls for a prediction of the flow velocities, and heat and mass transfer rates. The problem also poses an intrinsic scientific challenge of invoking an interaction of several natural forces. Due to these and other potential applications, chemical engineers have conducted some research in this area, but without seeking to alter g as an independent parameter. In Chapter C I we develop arguments to substantiate the merit of variable gravity in achieving an otherwise unobtainable broader range of the controlling nondimensional parameters.

In Chapter C II we have developed a matrix involving inertial, buoyant, surface-tensional and viscous forces to identify six different nondimensional numbers three of which invoke buoyancy. A three-dimensional force space diagram is developed here to point out the several regimes of control. An examination of the developed nondimensional numbers revealed several interesting applications.

As the Bond number is made to approach zero by gradually reducing the dimension of 'pool', and if a multitude of such zero-Bond-Number pools are put together next to one another, then one realizes a capillary porous body. Sponges, porous wicks, etc., are examples of capillary porous bodies; the disposition of any liquid absorbed by them is familiar to all of us to be independent of the sponge orientation with respect to the gravity vector. The scientific and technological importance of capillary porous bodies is also well-known. Even though the capillary body problem is fairly understood, use of capillarity to produce low-g-effects and use of low-g to produce capillary effects is not hitherbefore accomplished. The Spacelab offers an excellent opportunity to test the concepts in this production and characterization.

In general, manipulation of the relative role played by buoyancy forces may be done by varying the appropriate variables: the volume or linear dimensions, the density, density differentials and the gravitational constant. The range of variation achievable in a relevant nondimensional group by varying one or more of these participant variables is often a matter of economics, complexity and convenience. But it is well to remember that with the availability of the opportunity to use the Space Shuttle, one has the capability to realize long steady durations of reduced or programmed gravity conditions which would widen the range of phenomena that could be observed.

In Chapter C III, the heat transfer in the condensed-phase is examined in some preliminary detail of dimensional analysis. The dominant gravitational effects come via the Bond and Grashof numbers of the condensed-phase, and the Grashof number of the gas-phase. Chapter C IV deals with pool evaporation to point out that gravity enters the problem, rather strongly, through its influence on the heat transfer coefficients both in the liquid and in the gas-phase. This influence in its own turn manifests through Grashof numbers in the gas and liquid-phases. The pool evaporation problem finds a variety of scientific and practical applications. These applications range from humidification and defrosting, fog formation over lakes and rivers, misting of pilot visors, and other such environmental-control-related processes to a host of chemical process operations including the generation of vapors and their combustion.

Transient dispersion of fuel vapors into the quiescent atmosphere over an evaporating pool is the subject topic of Chapter C V. The dependency of adiabatic lapse rate for a dry air atmosphere on gravitational constant is well known theoretically for over three decades. As the gravity is reduced, the lapse rate approaches zero, according to this theoretical relation, thus leading one to expect a stabler atmosphere. There exist no experiments to date to verify and confirm this matter.

Also presented in ChaptersC V and VI is a solution to the transient convective-diffusive dispersion problem. The main finding was that when the leak rate of fuel vapors is high, the time required to attain a prescribed critical concentration at a given height above the evaporating (i.e., leaking surface is independent of the diffusivity and the width of the flammable domain is nearly independent of time. When the leak or evaporation rate is low, however, the critical time at any height is independent of the evaporation rate and the width of the flammable domain is significantly dependent on time. The evaporation rate being directly proportional to the free convective (i.e. g-dependent) heat transfer coefficient, one is thus lead to several questions with unknown answers. Two of these questions are: How precisely does gravity intrude into the vapor dispersion problem? What then would be the role played by gravity in determining the time to attain flammability limits at any height and the width of the flammable space belt? Only further analyses and experiments hold the answers. These experiments are again expected to benefit immensely from the essential environment provided economically by the Spacelab. The large-time solutions especially require a verification which is possible only in the Spacelab.

Transignition Processes:

These are discussed in Chapters C VII-X.

Chapter C VII: Ignition of Fuel Pools That are Initially Above the Flash Point;

C VIII: Ignition of Fuel Pools That are Initially Below the Flash Point;

C IX: Flame Propagation Over Liquid Pools That are Initially Above the Flash Point; and

C X: Flame Propagation Over Liquid Pools That are Initially Below the Flash Point.

In Chapter C VII, we explored the ignition characteristics of the temporally propagating combustible space over a liquid fuel pool which is initially above the flash point. Different ignition sources are considered to find those aspects of the problem which are influenced by gravity and, among them, those aspects which seem to benefit especially from the Spacelab experiments.

Concerning ignition by heated wires, an equation is derived to give the wire diameter and its temperature which would ensure ignition in a given environment. According to this equation, ignition is possible with a thinner wire if the gas conductivity, volumetric heat capacity, temperature difference between the wire and the ambience, and gravity are lower; and if the gas viscosity, heat of combustion and preignition reaction rate are higher. The underlying reasons are quite simple; any circumstance which would reduce the heat loss rate relative to the heat production rate is conducive to easier ignition. Whereas most of these intuitively expectable ignition characteristics are fairly well-confirmed in experience, no explicit verification of the influence of gravity is made to date thus warranting experiments in low-g. However, since the time-to-ignition is a sensitive (and usually long) parameter, most of the earth-based low-g techniques fail to provide long enough durations to let things settle to an equilibrium to isolate ignition characteristics unequivocally. Spacelab is expected to offer an excellent possibility to deal with this matter meticulously.

An interesting dilemma arises in the limit $g \to 0$ when keeping everything else constant, ignition must be possible with an infinitecimally thin wire (or particle), for then the reduced convective flows reduce dissipation of heat. There must in actuality, however, exist a breakdown of the convective-heat-loss-based hypotheses altogether since the events culminating in ignition then are quite strongly controlled by diffusional processes. This matter of determining the threshold of convective control could only be settled by prolonged, programmed low gravity experimentation which is only possible in the Spacelab.

There are two interesting auxiliary applications, of the heated wire problem in reduced gravity. First, if the wire were placed in a reactive gas mixture, the heterogeneous catalytic reactions at the surface of the hot wire are sensitive to heat and mass transport which are profoundly dependent upon the level of gravity. A thorough understanding of this surface phenomenon with possible explanations of various reaction mechanisms has so many down-to-the earth practical applications that an attempt to list these applications here is unnecessary.

Second, King's equation which is used universally in hot wire anemometry becomes invalid at the ambient velocities of the order of one meter per second or lower. This departure is long suspected to be a result of gravitational flows and their cooling but no scrupulous verifications of this suspicion seem to exist both in theory and in experiment. If our heated wire were situated in an inert gaseous medium in a 'wind-tunnel' where the velocity of flow could be varied at different gravitational levels, the data of power input to the wire required to keep the wire temperature constant will be of extreme utility in resolving this ambiguity in a highly practical problem.

Returning now to the ignition-by-heated-wire problem, gravity intrudes not only via the convective heat losses discussed above but also through its effect on the dispersion of vapors and formation of combustible space near the wire. In Chapter C VII we present an equation to witness the overall role of g that may be expected on theoretical grounds alone and that needs confirmation via Spacelab requirements.

If we are concerned with ignition by pilot flames or electric sparks, the predominant gravitational effect comes from the dispersion problem. The reader is referred to Chapter C VII to gain further information on this topic.

In Chapter C VIII we examine the case of hot wire ignition with the wire being placed quite close to the fuel surface. The physical concept is depicted and a dimensional analysis is conducted to show how the imposed nonuniform surface heating produces surface-tension flows which in turn cause the liquid surface to bulge upwards directly under the wire. As a result, the heating becomes much more intense and nonuniform. This peculiar phenomenon has been considered but in one existing investigation [22]. Chapter C X extends this problem to the development of steady flame spreading, discusses the importance of surface-tension and buoyancy in controlling the combustion, and shows the potential value of low gravity experiments.

The final transignition process we have considered is the flame propagation over liquid pools (Chapter C IX and C X). Layered gas mixtures are known to support an unusually fast flame propagation. The topic is of superb relevance in such practical problems as fire safety in mine roadways, abandoned tunnels and in structural corridors. At least part of the behavior may be explained on the basis of the generation and suppression of turbulence due to gravity which is accountable through a Richardson number. The current earth-based practice of obtaining a range of Richardson numbers involves independent variation of all the variables entering into its definition except the gravity constant. Spacelab experiments will permit an extra degree of freedom through variation of g to realize a broader range of Richardson number for investigation.

Furthermore, the literature shows that the flame propagation speed is strongly determined by the radius of curvature of the leading nose of the flame. It seems reasonable to expect gravity to exert some influence on the geometric disposition of the flame by intruding into the transport mechanisms. Thus the elucidation of the observed unusual propagation speeds requires, or at least benefits from, Spacelab experiments.

In galleries of finite length and finite height, flames are known to always exhibit an accelerative behavior. This behavior is apparently due to gravity. Little has been done to pin this point down.

If the fuel temperature were below its flash point, (Chapter C X), surface-tension forces come into play in the process of preheating of the liquid. Whereas several investigators have looked into this problem, the role played by gravity in either accentuating or suppressing these surface-tension-flows is not explicitly studied. An understanding of this role is certain to yield a more lucid picture of the complex phenomena whose interactions culminate in the spreading flame.

Postignition Processes:

The topics studied in this program under this title are presented in Chapters C XI - XIV:

Chapter C XI: Fully Developed Pool Burning in a Quiescent Environment;
C XII: Flame Size and Shape; and
C XIII: Extinguishment,
C XIV: Microfire.

Chapter C XI considers the rate of fuel consumption by combustion over several ranges of pool diameter. The mechanism of heat feed-back, the parameters of relevance and their gravity-dependence are discussed; and the importance of delineating this dependence is discussed.

Chapters C XII and XIII deal with flame size, shape and extinguishment. While gravity plays a dominant role that needs verification, it is important to note two points related to the smokiness and radiant power of flames under reduced g. First, gravity is expected to tamper with the so called preferential diffusion of select chemical species in the flame. Preferential diffusion is known to be one of the causes of the partial combustion and the consequent soot formation in flames. Second, due to the altered flame shapes and characteristic velocities, particulate products of combustion experience a residence time altered by gravity in the hot spatial zones. This altered residence time has strong influence on both the completeness of combustion and the radiant emission of the flames. The state-of-the-art in both these areas is so primitive that Spacelab experiments promise to yield pioneering data which would set the tone of future progress in efficient combustion of fuels.

In chapter C XIV we have developed the concept of microfire. In this concept, we preserve the relative importance of buoyancy, viscous and inertial forces invariant between the earth-based prototype and the model in low-g. By so doing we will be able to simulate the combustion of minute particles of fuel on earth with experiments in space on larger 'particles' which will permit detailed probing measurements of the flame structure.

The particle combustion problem is of critical importance in both energy and pollution applications. And yet, a detailed scrutiny of the participant mechanisms of particle and droplet combustion is close to impossible due to two reasons: First, experiments on vanishingly small bodies do not permit detailed probe measurements of the combustion and flame characteristics; second, the minute particles give vanishingly short life-time for probe measurements even if the probe measurement technology provides carefully (and magically?) designed probes. Experiments at low gravity on larger particles which simulate the earth-based minute particles are expected to alleviate both these headaches via the increased spatial and time resolution without any change in the kinetics of the system as would be the case with modifying the ambient pressure.

Whether or not microfires are possible can only be determined by actually trying to produce them under low-g conditions in the Spacelab. In Chapter C XIV we developed a set of modeling rules applicable to the microfire and also raised a mosaic of questions which need answers. One of the most important of these questions relates to the existence of a lower-limit threshold gravity level below which combustion is not possible.

This threshold issue is explicitly considered in Chapter C XIII on Extinguishment. A simple thermal imbalance argument applied to the flame leads to an extinguishment criterion. This criterion points out that as the gravitational acceleration is reduced, the flame resists extinguishment even at lower oxygen concentrations. There exist no data whatsoever to prove or disprove this implication. Experiments in the Spacelab provide well-defined g-values for long enough durations to obtain the necessary data which are crucial not only to learn more about effective fire safety in spacecrafts but also to develop a clear understanding of the important concept of microfire and of the basic nature of extinguishment itself.

Potential Experiments:

The scrutiny of various physiochemical processes involved in the burning of fuel pools, and of the role played by the gravitational constant, as presented in Sections C and D of this report, leads to identification of the following specific Spacelab experiments. These experiments in which gravity is employed as one of the primary independent variables promises to yield considerably valuable information of both practical and scientific merit.

1. Evaporative Convection in the Condensed-Phase;
2. Transient Diffusive-Convective Dispersion of Vapors in the Gas-Phase;
3. Ignition of Fuel Pools That are Initially Above the Flash Point;
4. Ignition of Fuel Pools That are Initially Below the Flash Point;

5. Flame Propagation Over Liquid Pools that are Initially Above the Flash Point.

6. Flame Propagation Over Liquid Pools that are Initially Below the Flash Point;

7. Character of Fully Developed Pool Flames;

8. Conditions of Pool Fire Extinguishment;

9. Definition of Liquid Fuel Flash Point, an Intrinsic Property;

10. Surface-Tension-Driven Flows, in General;

11. Effect of Gravity on, and Definition of, Flammability Limits;

12. Study of Carbon Particle Combustion by Employing the Concept of Microfire; and

13. Calibration of Hot Wire Anemometers in Low Gravity.

These experiments are neither all-inclusive nor prioritized, but just those whose impacts are strong enough to prompt consideration for their conduct in the Spacelab.

C-2

E. EXPERIMENTAL JUSTIFICATION

General Comments on Simulation:

Because gravity-dependent forces usually appear in our considerations in the form $\rho g d^3$ of the density or density differentials, gravitational constant and the linear dimension cubed, it is conceivable to control in an experiment the relative intensity of these forces by adjusting one or more of these variables. It is also possible to adjust gravity forces relative to other forces by suitably manipulating the magnitude of these 'other forces'.

For example, the gravitational force may be reduced relative to the capillary force by reducing the Bond number $Bo = \rho g d^2/\sigma$. This may be done by reducing ρ, gravity g or dimension d or by increasing the surface tension σ [5]. Porous wicks and sponges to hold liquids in any desired geometrical form illustrate the role of small pore size d which is in essence same as that of a reduced gravity constant g. Similarly, gravitational forces may be reduced relative to inertial force by increasing the Froude number $Fr = \rho V^2/\rho g d$ which may be done not only by reducing g and/or d but also by increasing the velocity V. A reduction in the Grashof number $Gr = g d^3 \rho^2 \beta \Delta T/\mu^2$, as an additional example, reduces the gravity force relative to inertial and viscous forces. This reduction again may be accomplished equally well by reducing gravity g, or by reducing the density ρ [33,36,37] and the linear dimension d [5].

There are, however, practical constraints in employing indirect methods of simulating low-g conditions. Among these constraints are the following:

(1) Probing difficulties: It is obvious that increasing difficulty is encountered in placing various measurement devices in an experiment as the scale of the experiment gets progressively smaller. The disturbances caused by the presence of the probes and their supports also become progressively

and unacceptably severe.

(2) Physical and Chemical Limitations: As the density is progressively reduced to bring about the same effects as brought by the reduced gravity, certain physical and chemical limitations are approached. Examples of the physical limitations may be seen by considering the role played by pressure as a basic thermodynamic property of the working fluid and as an essential factor in the definition of a continuum fluid. Examples of chemical limitations may be identified by considering the role played by pressure in determining the reaction kinetics and mechanisms, no matter whether they are simple or complex.

Heat transfer mechanisms, which are relevant not only to maintain combustion but also to suppress combustion, also suffer with the intrusion of slip-flow effects (Knudsen free molecule flow effects) as the gases become rarified and non-continuum. If reduced gravity conditions were sought to be obtained by reducing the density differentials, a whole set of novel heat transfer problems are encountered in the limit of vanishing driving potentials. These novel problems pertain to systems only slightly perturbed from their equilibrium states.

(3) Short Life-Times: An examination of the time scales of interest in thermal response of the condensed-phase, vaporization, diffusion and mixing in gas-phase and combustion of fuels indicates that small-scale experiments last far too briefly to permit the required measurements. The availability of suitable measuring tools with acceptable precision and accuracy as well as fast response is a matter of separate but related concern.

Consider the condensed-phase hydrostatics and dynamics, for an example. Suppose one wishes to employ Bond-number modeling. Then to preserve the Bond number $\rho d^2 g/\sigma$ invariant with a particular liquid, $d^2 g$ is to be kept invariant i.e., $d \propto g^{-1/2}$. If the Bond number considered is much greater than unity, that is in gravity-dominant regime, the characteristic time $t \propto (d/g)^{1/2}$ which with Bond model becomes $t \propto d^{3/2}$. Similarly, if Bo is much smaller than unity, that is in capillarity-dominant domain, $t \propto (\rho d^3/\sigma)^{1/2}$ which for a particular liquid reduces to $t \propto d^{3/2}$ again. Clearly this 3/2-power relation is valid for all Bond numbers. Then, a reduction of length scale by a factor of (1/10) reflects in a characteristic time reduction by a factor of $(1/10)^{3/2}$ or about (1/30). This reduction can pose formidable measurement, accuracy and response problems.

Similarly, where the gas-phase convective processes are attempted to be modeled by preserving Grashof number $gd^3\ \beta\Delta T\rho^2/\mu^2$, $g \propto d^{-3}$ and the response time is of the order $t \propto \mu/(\rho g d \beta \Delta T)$ so that $t \propto 1/gd \propto d^2$. A 1/10th reduction in the scale of the experiment then cuts the time scale by a factor of $(1/10)^2$, that is by 1/100 th. By considering modeling of other aspects, in a similar manner, the headaches associated with reduction in the linear scale of the experiment to simulate reduced gravity may be clearly seen through the more drastically reduced characteristic time.

(4) Visual Observations: Visual and photographic observations, likewise, also become immensely difficult or impossible due to the necessity of minute dimensions to be viewed in brief time frames. Speed and resolution, two often conflicting parameters of photography, are not always available to record an experiment.

Keeping these and other similar limitations in mind, some of the currently known low-g simulation techniques are briefly discussed below.

Simulation Techniques:

There appear to be at least the following eight different methods of varying the relative importance of gravitational forces in various combustion-related processes:

(1) Observing the processes as they occur on bodies of progressively smaller scale;

(2) Using other extraneously applied and controllable body forces, such as magnetic forces, to nullify part or all of the gravitational forces;

(3) Using centrifuges upon the arm of which the body is allowed, or made, to slide;

(4) Using various pressures in the fluid to alter the density;

(5) Using dyes in water tank, the dyes being chosen variously buoyant relative to the working fluid, viz: water;

(6) Conducting the experiment in a freely falling chamber; using counterweights to achieve different desired g - levels;

(7) Conducting the experiment in an aircraft whose flight trajectories are preplanned to realize the desired g-variation; and

(8) Conducting the experiments in a spacecraft.

Each of these methods have their intrinsic advantages and shortcomings in terms of feasibility, simplicity, cost, available duration, intrusion of unforeseen and undesirable other forces and such other factors. The first five items listed above may be arbitrarily placed into a class entitled 'bench-testing'.

Classical modeling of combustion phenomena both in power and propulsion applications and in fire research involved scaling 'down'. To this effect, method 1 above employing variations in the characteristic linear dimension has been used for heat transfer studies of free convection [38] for diffusive combustion studies [5,39] as well as for liquid sloshing studies [4,40]. This method is by far the simplest and cheapest even though the range possible for variation is rather restricted. As progressively smaller linear dimensions are considered instrumentation problems become serious and useful data become unobtainable.

What with the availability of sophisticated ultra-centrifuges in NASA, method 3 seems to be attractive. However, unwanted intrusion of forces such as Coriolis forces might complicate the issues under study. In method 4, highly suitable for study of gas-phase convection processes, the ambient pressure is varied to achieve changes in the Grashof number. Saunders [36] used this approach to study free convective heat transfer. Williams [37] conceived this method to be suitable for studying free convective diffusion flames. deRis, Kanury and Yuen [33] developed the pressure modeling theory of fires and demonstrated its validity in describing the combustion of vertical surfaces. Kanury [34] reported pool combustion experiments in which the burning rates and radiant output of flames over a variety of plastics are correlated with ambient pressure.

Little has been done in the use of dyes to quantitatively alter buoyancy forces. Much of the available work deals with flow visualization with neutrally buoyant dyes [41-43]. There seems to be a virtually unexplored technique here not only in devising ways of producing and dispersing dyes of different densities relative to the working fluid but also in actually simulating the gravity-driven flows to obtain a quantitative understanding of the phenomenon. Conceptually similar to these dye experiments are the few known salt-water-tank studies.

Free-fall simulation of low-g has been reported in the literature quite extensively. The two most noteworthy groups working in this area are from Japan [44] and US NASA-Lewis Research Center [45]. The time available in a free-fall facility is of the order $t \propto h^{0.5}/2.2$ sec, h being the height of fall in meters. A height of 5 meters thus gives about one second of fall time. In order to double this time, the height has to be increased to about 20 meters; and to triple it, nearly 45 meters. The air resistance to the falling capsule becomes a severe problem with large fall heights. A double-capsule system, in which the outer capsule acts as a drag shield, is employed to overcome this problem. Another technique used is to drop the capsule in a near vacuum as is done in the Lewis' 500 foot facility.

Whereas a free-fall gives an essentially zero gravity (i.e., gravity of the order 10^{-7} g_o), counterweights may be employed to attain various fractional gravities (i.e., g lying between 10^{-2} - 10^{0} g_o.). One of the most important things to remember in free-fall experiments is that the characteristic time of the phenomenon under study has to be less than the fall time. This requirement is not always met, especially in experiments dealing with liquid fuel evaporation, vapor/air mixing and combustion. Thus the finite and short duration of the low gravity ends up to be one of the mortal shortcomings of the free-fall technique.

Aircrafts executing Keplerian flight trajectories are used to obtain longer durations of low and programmed gravity conditions. Kimzey [46] used this technique to study combustion of various polymers. Free-floating capsules are normally used to isolate the experiment from the air frame. Maneuvering the aircraft in such a manner as to avoid collisions between the experiment capsule and the airplane walls is not the easiest of the tasks of the pilot.

Techniques of Flow Visualization and Measurement:

One of the most important measurement problems in combustion involves mapping out both qualitatively and quantitatively the flow field in and around the flames. Particularly in studies of burning liquid pools the problem becomes even more challenging because both the condensed-phase and gas-phase flow fields may be relevant and must be analyzed. The condensed-phase flows are usually quite feeble and thus call for elegantly sensitive techniques.

The currently available techniques may be broadly categorized into four classes.

1. Point Techniques: Examples include the classical pitotstatic probe, hot-wire anemometer, Laser-Doppler anemometer, etc. The distinguishing feature of point techniques is that the velocity (components?) is measured to the desired detail at a specific point by generally placing the sensor of a probe precisely at that point. LDA is an exception to this rule in that it does not have a sensor *per se*; two laser beams are made to intersect at the point of interest. Thus LDA may also be classified as a point optical technique.

2. Tracer Techniques: Examples include the technique using ions as tracers, illuminated or luminous particle methods, smoke methods, bubble methods, etc. To introduce minute quantities of highly visible, easily trackable and immensely agile tracers into the flow field and to follow their movement photographically is the basic concept here.

3. Optical Techniques: Schlieren, shadowgraphic and interferometric techniques are prime examples. Mainly suitable for mapping out the density distributions, these techniques can be useful to extract the velocity field indirectly for certain types of flows in which the momentum and energy equations and their boundary conditions exhibit common features. The fundamental idea underlying almost all optical techniques is that density gradients in a flow field are always associated with gradients in absolute refractive index which in turn predictably affect the traverse of a beam of light.

4. Other Techniques: Miscellaneous techniques such as light screen techniques, electrical discharge anemometry, LDA, light absorption and scattering by tracers, etc. may be placed in this category.

The particular technique suitable for a particular situation has to satisfy the special requirements of fast response, sensitivity, ruggedness, resolution, noninterference with subject flow, delineation of three dimensional effects, irresponsiveness to extraneous vibrations and disturbances, simplicity of setting-up, portability of the equipment, and others. The feat of meeting these, often conflicting, requirements is not always an easy one and is truly a test for the experimentor's elegance and creativity.

Condensed-Phase Flows:

Since the flows involved here are usually quite feeble, sensitivity is critical. The classical Pitot tubes seem unsuitable, for they are neither sensitive enough nor responsive enough, leave alone their obesity and physical crudeness. The hot-wire anemometer is suitable for point measurements due to its fast response and sensitivity but the probe supports may seriously interfere with the flow field. Schlieren, shadow and interferometer methods are extremely suitable for qualitative visualizations but suffer with their: extreme sensitivity to extraneous disturbances, bulkiness of the set-up and inability to accurately account for curvature and other three dimensional effects. These optical techniques thus seem usable in earthbased laboratory work in preparation for the more sophisticated Spacelab research.

Particle track techniques pose special problems in studying flows in liquids due to the liquids' higher density and viscosity. It is extremely difficult to find particulate materials which are neutrally buoyant in liquids for observations in the bulk. In order to note and measure the liquid surface deformations and movements, however, particle techniques seem adequately suitable.

Laser doppler anemometry seems to be extremely suitable for liquid flow measurements point-by-point in good quantitative detail. Portability seems to pose no special problems with LDA. To map out an entire flow field, however, the current state-of-the-art seems to leave something desired. A possible future improvement in LDA technology which would expand the LDA utility from point measurement to field-mapping perhaps involves development of a 'scanning system' somewhat superficially similar to the TV scanning in concept. Current needs seeking to gain intermittent but complete qualitative picture of the entire flow field are not benefited by the present LDA state-of-the-art.

Injection of dyes to observe the nature of liquid flows is a technique as old as Osborne Reynolds' discovery of turbulent flow in a pipe. Recent developments are dramatic. Following Baker's technique [41], Husar and Sparrow [42] and Lloyd and Sparrow [43] modified the dye technique by invoking electrolytic titration processes. (Note that Professor J. R. Lloyd is a Notre Dame scientist participating in the conduct of the present project research in collaboration with Kanury.) The technique uses water as the working fluid. A small quantity (0.01 percent by weight) of thymol blue ph indicator is added to distilled water, titrated with sodium hydroxide to a ph of about 8, and then made acidic by adding hydrochloric acid. The color of this acidic fluid is yellow. If one now impresses a d.c. voltage of 4-10V on the fluid layer, a proton transfer is triggered which changes the ph value, thus changing the yellow color to blue. The color change is demonstrated to vividly portray the details of the flow patterns in the liquid.

Bubble techniques are also eminently suitable to follow liquid-phase movements. Schraub and his colleagues at Stanford [47] and Mattingly [48] at David Taylor Model Basin developed a hydrogen bubble technique for use in visualizing low speed flows in hydrodynamic tunnels. The technique basically involves delivery of a high voltage pulse to a cathode filament (usually a 0.0015 inch platinum rod) suspended in the flowing electrolytic fluid. With each pulse, a string of tiny hydrogen bubbles is generated at the filament surface, and detached and swept away by the moving fluid. The bubbles are usually small enough to permit neglect of bubble buoyancy relative to convection. The velocity field (viz: speed as well as direction) can be determined by following the bubble motion which in steady state manifests with the string of bubbles in the form of a well-defined profile. In order to control the bubble population at the best desirable level, Glassman [49] at Princeton coated the platinum rod with silica by baking it in a flame and then produced cracks in the silica coat to the desired extent.

In conclusion, thus, it seems possible to capture the qualitative picture of the liquid-phase flow patterns by using optical techniques, dye tracer methods and by hydrogen bubble technique. The bubble technique is promising in that it is capable of giving both qualitative and quantitative data in both the earth-based and Space Shuttle laboratories. Laser doppler anemometer is expected to be the most sophisticated quantitative tool available today, even if its ability to compose the flow field in entirety qualitatively is severely restricted. Scanning techniques to render LDA a universal desirability are suggested for future development.

Gas-Phase Flows:

The techniques discussed so far in this chapter serve fairly well as an introduction to the gas-phase flow visualization and measurement problem. In some respects, this problem is simpler than that of liquid-phase and yet more difficult in other respects. The velocities of interest are larger, the density variations are more severe and the possibility of tracer contamination effecting the fluid properties less crucial.

Ion tracer anemometry offers an attractive tool. At a known place in the flow, and at a known time, a differential volume of the gas is ionized; at a measured later time, at a known distance downstream, a detector counts the ions and enables direct calculation of the true flow speed. The technique measures speed but not velocity; and the measured speed is an average, not localized and not instantaneous.

Particle tracks are widely used to follow flows in flames. A small particle of matter follows with more or less fidelity the fluid motion in which it is floating. The most faithful particle has little mass, little surface and is stable both chemically and physically as it passes through the high temperature field of the flame. Upon injecting into the flow of a fluid whose viscosity is μ, a particle of mass m and diameter d takes, according to Stokes' law, a time of the order $(m/3\pi\mu d)$ to pick-up the fluid speed. Aluminum and magnesium flakes of size 1 to 5 microns are known to have been used in wind tunnels. Thomas and Heselden [50] used thistledowns to follow and measure air entrainment in large open fires. Orloff [51] used metaldehyde (a pellet used by the Swiss to ignite the domestic oil-burning heaters) which sublimes into fine flakes in order to visualize free convective flows in an enclosure.

In order to measure the local instantaneous velocities of air, Liepman [52] used electric discharges. The basic idea of electric discharge anemometry (EDA) rests on the fact that air not being a perfect insulator permits passage of electricity between electrodes. The current depends on variables such as field strength, electrode material, spacing, configuration, production of ions by such things as a flame, the pressure and the air velocity. If all but the last of these are held fixed, the current gives a measure of velocity. Experience indicates that the higher the air velocity, the lower the current.

The use of smoke to trace air flow patterns is primitive but simple and effective to depict the flow visually. Finally, in conclusion, portrayal and measurement of flow fields in gas-phase is a relatively simpler matter to a skilled experimentator than doing the same in condensed-phase. Sophisticated tools are now available and are constantly being improved. That the gas-phase in our pool evaporation problem constitutes the ambience allows us the use of an almost unlimited set-up space for any flow monitoring equipment.

The Need for Space Experiments:

In our analytical justification Section D, we have evidently seen that there are, in concept, several aspects of the pool burning problem which would benefit immensely by studies which focus attention on gravity as an important independent variable. These theoretical bases for recommending research in space have also to be tempered with any experimental bases to strengthen the recommendations. The objective of this brief is to develop these experimental justifications.

A given theoretical hypothesis or a concept is only as good as it is verified by the relevant experimental data. The experiments themselves could be either incidental (or ad hoc) observations of Nature or deliberate designs (emulating the Nature) in a lab. The laboratory may be either here on earth or aboard a spacecraft. Three sequential questions then arise:

- Is the considered hypothesis (or concept) worth (scientifically and/or technologically) testing by experiment?
- If the answer is in the affirmative, then, are deliberately planned laboratory experiments needed?
- If the answer once again is in the affirmative, does this laboratory need be placed in a spacecraft.

Section D of this report contains nearly a dozen gravity-related hypotheses related to combustion of liquid fuel pools which hold enough scientific and practical merit to warrant experimental confirmation (or denial). There are some hypotheses that relate to the existence of limiting conditions the establishment of which requires experimentation.

Because gravity-dependent forces usually appear in our considerations in the form of the product of density, gravity and volume, it is conceivable to control the relative intensity of these forces in an experiment by controlling one or more of these three variables. It is also possible to adjust gravity forces relative to other forces by suitably manipulating the magnitude of these "other forces". Traditionally, earth-based experimental studies of problems involving gravitational body forces employed variations in pressure (i.e., density), linear dimensions of the body under study and the "other forces" to understand the gravity-controlled phenomena. For example gravitational force may be reduced by choosing to experiment with bodies of smaller linear dimensions and with ambient atmospheres of low pressures. Or, gravitational forces may be reduced: relative to capillary forces by reducing the Bond number; relative to inertial forces by increasing the Froude number; or, relative to inertial and viscous forces by reducing the Grashof number.

There are, however, practical constraints in employing these and other clever little indirect methods of simulating low-g (or high-g) conditions. These constraints relate to probing difficulties, hazarding inadvertent alteration of the involved chemical reaction mechanisms, coping with short available life-times of the experiment, and difficulties related to visual and photographic observations.

Relatively few studies, and only relatively recently, have sought to employ the extra degree of freedom offered in an experiment by the controlled variation of the gravitational acceleration. Earlier in this section, the various ways of simulating low-g conditions in earth-based laboratories are summarized, each of these "ways" possessing their intrinsic advantages and disadvantages in terms of feasibility, simplicity, cost, available duration, intrusion of undesirable or unforeseen extraneous forces, etc.

All the various low-gravity concept studies discussed in the current project have one important feature in common. In order to do a well-defined experiment, the duration of the reduced or zero gravity condition has to be longer than the characteristic time of the phenomenon under study. Various combustion phenomena exhibit rather long characteristic times. For example, the time of formation of a stable liquid surface varies, as developed in Chapter C II as (pool dia/evaporation velocity) if the inertial forces are controlling; as square root of (gravity/diameter) if buoyant forces are controlling; as square root of (liquid density x diameter cubed/surface tension) if capillary forces are controlling; and as (density x diameter squared/viscosity) if viscous forces are controlling. Most notable from these derivations are the following points:

1. The evaporation rates are quite low (v is 2 mm/min or lower [5]) in the pool burning experiments. If only evaporation occurs without combustion, these rates are even lower (by about an order of magnitude) than this value. Thus the case of inertial-force-controlled situation indicates that the characteristic time of evaporation with and without combustion is extremely long.

2. In as much as we have to contend with manageably small pans and as the gravity has to be low to capture the anticipated affects, buoyancy-driven flows exhibit reasonably short characteristic times. But one has to be extremely careful in this deduction since little is known of the life-time of fluid mechanical disturbances that are extraneous to the experiment.

3. Employment of any reasonable diameters of the pan to burn the most usual liquid fuels results in a time constant of formation of 1-10 sec, the dependency being $t \propto (\text{diameter})^{3/2}$. (cf. Chapter C II).

4. The ignition delays under normal gravity conditions are known to be in the 1-10 sec range as well. Similar in magnitude are the extinguishment delays and flame spread characteristic times.

5. Expecially when dealing with the flame spread process, there exists,

due to size constraints, a transient time in which the propagating flame accelerates to its eventual steady state of propagation. This transient time requires longer, wider pans and hence longer times in low-g for any rational study of spread rates. Nominal normal gravity distance and time are about 10 cm and 10 seconds [23].

Other similar arguments may be developed to obtain a feel for the magnitude of the characteristic times of different physicochemical processes related to pool burnin at different gravities. In general, as a back-of-the-envelope approximation, most characteristic times lie in the range of a few seconds to a few tens of seconds.

The various techniques employed on or near the earth's surface to simulate low or zero gravity become unsuitable for combustion studies. (cf. simulation techniques). Aircraft flying Keplerian trajectories pose problems in available test time ($\simeq$ 20 seconds) and poor initial conditions (high g). Rockets present the problems of spin-up and spin-down (to quiescence) and size constraints. Also fuel loading under low-g remotely produces unforeseeable difficulties. Notwithstanding the short durations of effective experimentation ($\approx$ 10 seconds) the most sophisticated technique of achieving low or zero gravity conditions employs a droptower.

Thus the discussion leads to the use of spacecraft for low-g simulation. The increased available time would permit relatively larger experiments which are easier to probe and otherwise manage. Programmed gravity conditions are also then possible. Detailed observations and alterations of the conditions are possible thus making the spacecraft testing the ultimate answer to our quest to learn of the role played by gravity in the array of physics and chemistry problems related to pool combustion as discussed in our analytical justification.

F. SPACE LAB EXPERIMENTS AS CURRENTLY CONCEIVED

General Objectives:

The objectives of pool burning experiments in the Spacelab are to make;

- qualitative observations;
- quantitative testing of various gravity-related hypotheses; and
- quantitative establishment of the thresholds of (a) validity of several presently predictable phenomena; and (b) existence of several speculated heat/mass transfer and combustion modes.

The experiments have to be such as to be uniquely possible only in the essential environment of the Space. Both the qualitative and quantitative studies will relate to various aspects of the behavior of pools which are discussed in our earlier Chapters of this project. These studies must lead to a distinct advance in the state-of-the-art and science of combustion of liquid fuels. The aspects of the problem to be considered in the Spacelab include: the preheating, evaporation of the fuel, dispersion of the vapors, ignition by various means, flame spread, fully-involved burning characteristics as well as extinguishment. Fluid movement patterns in both condensed and gas-phases will have to be observed and measured. The fully-involved burning characteristics include the mass-loss rate, radiant heat fluxes, the flame shape, size and nature, etc. Liquids with initial temperature both above and below the flash-point have to be considered.

Whereas the quantitative data are expected to enable us to verify the expected or speculated phenomena, the qualitative observations will serve two specific purposes. First, they aid to consolidate the quantitative measurements in some detail, say via photographic visualization. Second, they will reveal some features, phenomena, and processes which have not been identified before in our project research.

The objective of establishing the thresholds of validity of various concepts and notions, and existence of different modes of combustion would in effect lead to identification of limiting combinations of conditions which would permit a particular phenomenon to occur. Not only new useful information but also novel unfamiliar notions are expected to evolve out of these threshold delineations.

Constraints of the Spacelab Experiment:

The pool burning experiment to be carried out in the Spacelab must fulfill certain inherent constraints. The experimental set-up has to be large enough to permit the planned observations and measurements, and yet small enough to (a) permit visualization through limited-view-angle photographic means and (b) assure a lack of hazard to the Spacelab and its crew in the event of a spill. The set-up has to be relatively insensitive to extraneous disturbances (such as g-jitter). It should require little or no calibrational effort in flight; and must be as much automated as possible to avoid potential human error, inconsistency and variance. These are but a few of the constraints. Similar other constraints will have to be thought out and incorporated into the experiment prior to its installation in the Spacelab experiment module. This, we expect will be done during the feasibility studies.

Specific Objective:

An examination of the list of potential experiments presented in the end of Section D of this report reveals that the pool set-up offers a broad range of fruitful investigations in the Spacelab. Attempting to arrive at a specific experiment whose goals are well-defined while at the same time seeking to preserve flexibility to allow study of several processes at a later time, the topics of ignition and flame spread have been chosen for the immediate consideration of preliminary experiment design and feasibility analysis. This choice, admittedly, is not without subjectivity. However, a carefully designed ignition experiment can be used for studying various facets of pool burning problem later, these topics being thoroughly discussed in Sections C, D and E. The specific objective of the current experiment design, hence, is:

> to design a fuel pool experiment apparatus for study of ignition process under a variety of prescribed conditions, such a design being versatile enough to accommodate future experiments on various other pool burning processes, especially the flame propagation.

Description of the Experiment:

Figure 10 shows a schematic of the experiment as currently conceived. The heart of the experiment, of course, is the pan which holds the fuel. A circular pan may be convenient in terms of fabrication, but a square or a rectangular pan is expected to present fewer three-dimensional complexities related to flow visualization and instrumentation. Flame propagation tests could perhaps be better done with a rectangular pan. The factors to be considered in the design of this pan will be discussed in Section G entitled Feasibility Questions.

The peripheral walls of the pan are visualized to be built of Mica which is optically transparent, chemically inert, highly heat resistent, insulating both thermally and electrically, and possesses low heat capacity. The veneer structure of Mica will permit as thin a wall as desired. (Mica is discussed thoroughly in Section G.)

An ignition wire of such length as to alleviate the end-effects will be placed in the gas-phase at a prescribed distance above the fuel surface, parallel to the fuel surface as shown. Also to be provided are probes or rakes of probes to measure temperature, composition and velocity in the gas-phase. One or two thermocouples will be placed strategically in the condensed phase as well.

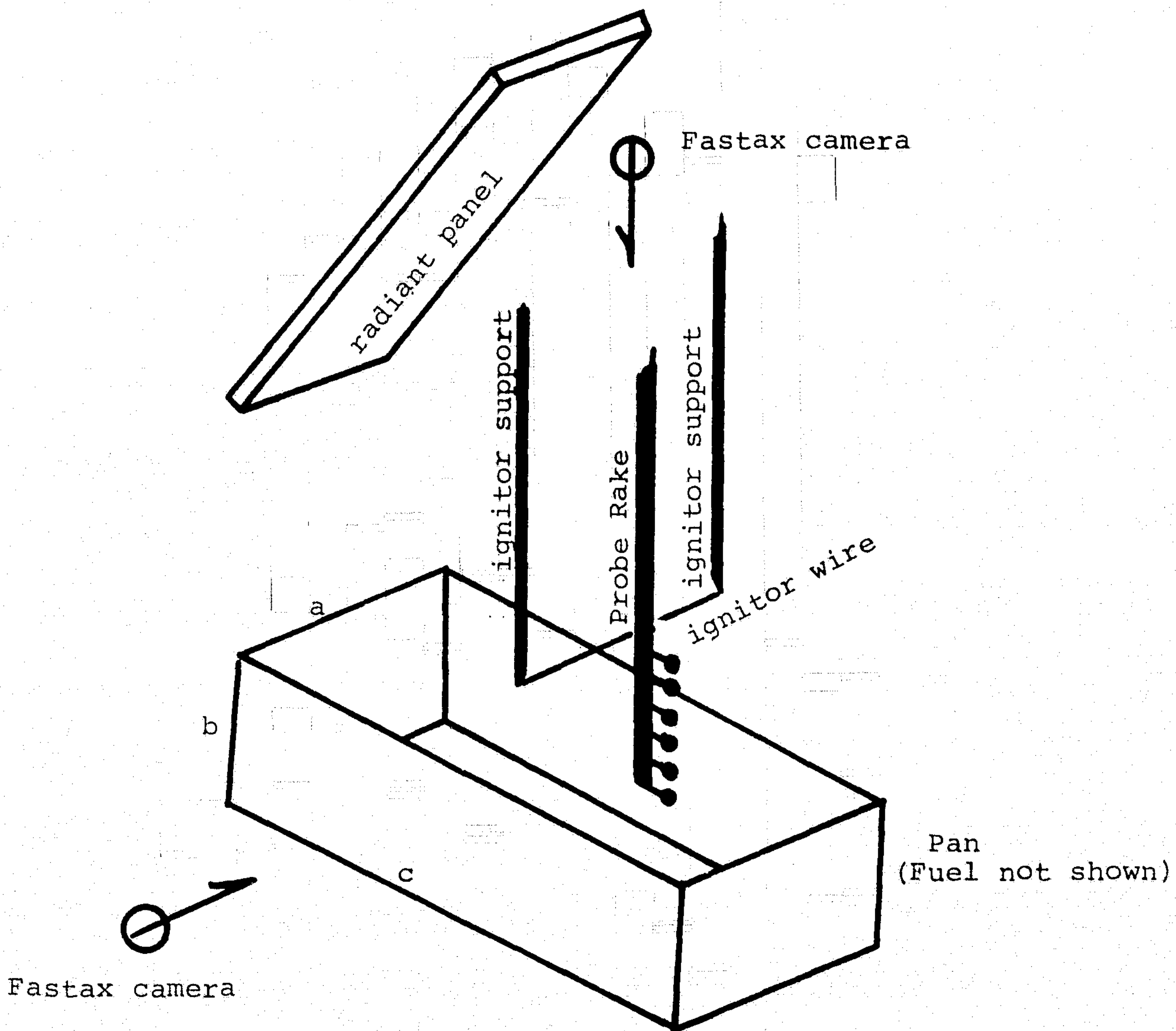

Figure 10 Experiment as Currently conceived

An external radiant panel with calibrated radiance versus electrical power input may be found desirable. This panel has to be so placed in the gas-phase as not to interfere with the gas flows while at the same time impinging uniform heat flux on the fuel surface.

High speed motion picture equipment are to be installed for visualization of flows in both the liquid and gas-phases. The special requirement of any needed seeding of these phases with a visible tracer (particles?) has to be met in some yet unknown manner.

Experimental Procedure:

The essential steps in the experimental procedure involve: setting-up the experiment, setting time-zero, waiting out and observing the formation time, and starting and carrying out the experiment to a prescribed completion. Intruding into this sequence of steps anywhere desired will be a safety check step and experiment termination.

The setting-up of the experiment involves calibration and operational checks, initialization of temperature and composition of the atmosphere, introduction of the fuel, initialization of the fuel temperature, etc. The time-zero setting involves turning on the camera(s), radiometer(s), bubble-generation wire or other tracer injection device, counters, data acquisition system, etc. Actuation of the external radiation source and the ignition source upon formation of stable condensed-phase state mark the start of the experiment. The safety check step includes a continuous or intermittent monitoring of the composition and temperature of the experimental chamber and emergency termination scheme. The termination step shuts off the entire experiment and automatically dumps the chamber contents into the space outside.

G. FEASIBILITY QUESTIONS

Objective of Feasibility Studies:

The pool evaporation/combustion study in the Spacelab obviously holds considerable merit from both analytical and experimental view points yielding data of much potential practical importance and impact. The rudiments of such an experiment as currently conceived are described in the preceding section. In the present section we discuss several feasibility questions related to developing this experiment into reality. These and other similar questions will have to be resolved in the course of feasibility studies and experiment development.

A design can become a futile exercise unless the satisfaction of the objectives and the needs of the original overall experiment can be met. Thus the goal of the feasibility studies will be to seek ways of achieving the gist of the planned experiment, and making the required observations/measurements. Alternative methods will have to be considered for their reliability, cost and ease of operation. Upon the conclusion of the feasibility study and upon conducting theoretical and practical analysis/development of several workable alternate solutions to the different facets of the Spacelab experiment, the experimental set-up will have to be shown as something real and something that could be incorporated into the Spacelab to study the planned combustion topics. Thus the objective of the feasibility study will be to: develop the currently conceived Spacelab pool burning experiment to a state where it can be installed in the Spacelab to carry out the planned concept studies. This development involves: choice of materials, fabrication, alternative methods of measuring various experimental parameters, accounting for the safety of the Lab and the crew, etc.

Strategy of Attack on the Problem:

The design of the experimental set-up will be carried out to facilitate study of not only ignition and flame spread but also other aspects of pool combustion. In the short term goals, both sub- and super-flash point cases will be considered. The sub-flash point ignition experiments will involve two steps: first, an inert liquid (water?) may be employed in place of the fuel to study the condensed and gas-phase flows induced by the proximate heated wire. Then the experiment shall be repeated with the fuel to study ignition. There seems to be reason to believe that the physical flow patterns remain the same (or similar) no matter whether the liquid is inert or reactive. If this were so, the inert liquid experiment will serve as a sort of conceptual calibration of the physics of ignition, thus making it possible to delineate physics from chemical aspects of ignition.

Whereas these sub-flash point ignition studies yield the detailed mechanisms of the processes contributing to ignition and lead to development of a theoretical model, the super-flash point ignition studies will yield lumped ignition/flammability characteristics such as minimum ignition energy, flammability limits and quenching distance. These characteristics are useful not only to feed into the engineering practice literature but also to verify the integrated predictions of the theoretical model developed in sub-flash point studies.

The entire accomplishment of the ignition studies will be the starting point of the flame spread studies both experimentally and theoretically.

Some Feasibility Issues:

The pan dimensions a, b and c shown in Fig. 10 are to be determined in the feasibility studies. The dimension a has to be large enough to alleviate two-dimensional effects and yet small enough not to jeopardize the safety of the ship in case of an accidental spill. The dimension b is determined by the depth dimension of the cell of flow induced under the combined influence of buoyancy and surface-tension. The dimension c again has to be no larger than necessary (due to safety considerations) but large enough to study flame propagation untampered by the domain of ignition and by preignition heating.

There seems to be a method possible for safe deployment of fuel while keeping the experiment simple. Clausius-Clapeoron equation of state suggests that a higher ambient total pressure results in a lower flash point (i.e., saturation temperature to realize a prescribed critical vapor pressure). Thus the liquid fuel at a safe low temperature may be transported and loaded into the pan at a low total pressure so that the fuel temperature is less than the flash point. Now if one wishes to study the super- flash point cases, simply raise the pressure of the ambience and the flash point will be lowered below the fuel supply temperature. The idea merits feasibility consideration by a careful consideration of Gibbs-Dalton law of partial pressures, laws of equilibrium vaporization, etc.

Another feasibility question relates to the effect of liquid surface (tension) curvature on the observed flow patterns. If one fills the pan 100%, the curvature could be eliminated but how to fill this fully and how sensitive the then formed surface is to minor disturbances are two issues of concern which have to be resolved in the feasibility study.

Tracers have to be dispersed in the fluids to optically observe the flow patterns. The nature of best suitable tracers and the manner of their dispersion remain to be determined in the feasibility study.

Whereas temperatures could quite conveniently be measured with thermocouples, the methods of measuring compositions (grab samples?) and low velocities (hot wire anemometers?) are not obvious and hence are expected to require serious feasibility examination.

The inert liquid for preignition experiments has to be chosen with due consideration of the compatibility of such properties as the viscosity, surface-tension, heat of vaporization, etc. This method of choice has to be developed in the feasibility work.

Ignition is customarily said to have occurred when an external source initiates a combustion wave which is capable of sustaining itself independent of the external source. The customary experimental definition relies on visual appearance of a self-sustaining flame. The question of 'what is ignition?' seems to be a fundamental feasibility issue.

Some Progress in Feasibility Studies:

In the final stages of the current project period, some of these feasibility questions were investigated. The most important progress in this investigation relates to the choice of the material with which the fuel tray is to be fabricated. Mica is identified as a promising material with its optical transparency, chemical innertness, high heat resistance, thermal and electrical insulation, and low heat capacity. The veneer structure of this material will permit as thin a wall as desired.

Mica is a general term applied to certain clay minerals composed of fine aluminosilicates. Physically it is composed of electrically neutral layers which move readily over each other, to yield properties such as flexibility, soapy feel and easy cleavage. Mica is of secondary geologic origin, i.e., it is formed as an alteration product of aluminosilicate rocks in an environment in which water is present, through weathering and sedimentation. Sheet mica is mined from pegmatites, which are often up to 15 feet in thickness and as large as 24" x 30". The flaky form is recovered from clay deposits, and is then suitably processed. There are many varieties of mica occurring in nature [53], the principal ones being Muscovite ($K\,Al_2(AlSi_3O_{10})\,(OH)_2$), Paragonite

($Na\,A\ell_2\,(A\ell Si_3O_{10})\,(OH)_2$), Lepidolite ($K\,Li_2\,A\ell\,(Si_4O_{10})\,(OH)_2$), Phlogopite ($K\,Mg_3\,(A\ell\,Si_3\,O_{10})\,(OH)_2$), Biotite ($K\,(Mg\,Fe)_3\,(A\ell\,Si_3\,O_{10})\,(OH)_2$), Margarite ($Ca\,A\ell_2\,(A\ell_2\,Si_2\,O_{10})\,(OH)_2$), Clintonite ($Ca\,Mg_3\,(A\ell_2\,Si_2\,O_{10})(OH)_2$) and Roscoelite.

As in other silicates, their structure is built around SiO_4 tetrahedra, having each, a central atom of silicon, with 4 oxygen atoms at the corners of a regular tetrahedron. Two planar layers of these tetrahedra are separated by a layer of magnesium, iron and hydroxyl or aluminum in an octahedral formation. The three layers thus formed are weakly joined to other such layer combinations, by cations such as K or Na. At these surfaces, the material cleaves easily.

Most micas are monoclinic, pseudohexagonal but a few are hexagonal or triclinic. Crystals are commonly tabular with prominent basal planes and hexagonal or lozenge shaped outlines, with edges intersecting at 60° or 120°. Optically most micas are biaxial and levorotary with moderate birefringence. Figure 11 shows the structure.

Physical Properties of Mica:

Muscovite is the most commonly used mica in the natural form. The perceptible physical properties are transparency and cleavability into fine sheets.

a. Mechanical Properties [54]:

1. Flexible and elastic sheets with specific gravity 2.7 to 3.1.
2. Hardness is 2.0 to 2.5 (Mohr's scale) Knoop Hardness around 90.
3. Modulus of elasticity = (20 to 30) x 10^6 psi.
4. Tensile strength = (40 to 50) x 10^3 psi.
5. Compressive strength = 150 x 10^3 psi.
6. Surface energy in vacuum is 4500 ergs/cm^2 and 375 ergs/cm^2 in moist air.

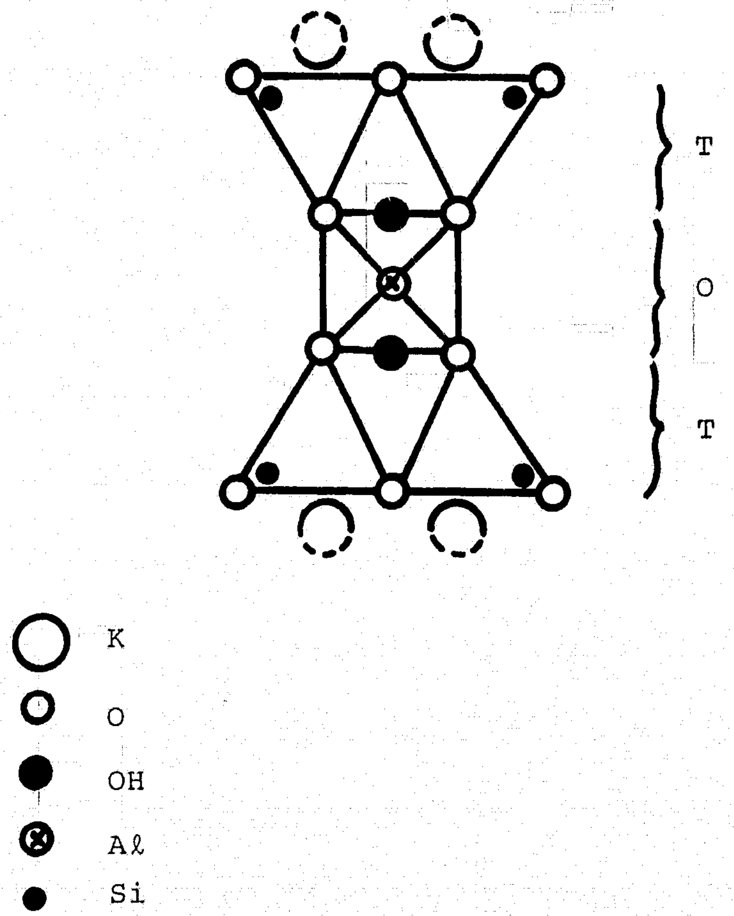

Figure 11 Crystallographic Structure of Mica [53]

b. Electrical Properties [54,55]:

1. Resistance = 10^{13} to 10^{17} ohms/cm. This decreases with increasing temperature and is near 10^{13} at about $400^{o}K$.

2. Dielectric Strength= 1000 v/mil

3. Dielectric constant = 5 to 9 at $70^{o}F$ & 1 MHz.

4. Dissipation factor = 0.0001 to 0.0004 at $70^{o}F$ and 1 MHz.

Note that the dielectric strength is not an accurate measure of electrical quality. The Q value is used instead, which is the reciprocal of the power factor. The power factor is the measure of loss of electrical energy in a capacitor in which mica is the dielectric. High quality mica has a minimum Q value of 2500 or a power factor of 0.04% at 1 MHz. The electrical insulation value is decreased by iron inclusion and hence dark colored mica is valueless as an insulator.

c. Thermal Properties [56-58]:

1. Linear thermal expansion is from -2.0% to +0.5% at about $900^{o}K$.

2. Heat of formation for muscovite at $-298.15^{o}K$
   $= -1421.2 \pm 1.3$ kcal/mole (from elements) and
   $= - 55.9 \pm 1.3$ kcal/mole (from oxides)

3. Thermal conductivities were measured [57] from 100^{o} to $1000^{o}C$ parallel to, and perpendicular to the basal cleavage. The results were that parallel to the plane, k decreases with increasing temperature and perpendicular to this plane, it increases with increasing temperature. Alo $k_{\parallel} \simeq 5.5\, k_{\perp}$. For micas in general, thermal analysis shows wide diversity. For well crystallized materials approaching the ideal muscovite composition, loss of water apparently occurs over a wide range of temperatures up to $1000^{o}C$, without major reorganization of the structure. It is speculated that the heat resistance

would temporarily be improved by this. Subsequent changes at higher temperatures seem to depend considerably on the precise chemical character of the mica. Mullite ($3A\ell_2O_3 \cdot SiO_2$) and corundum are the principal decomposition products, but they appear in very variable amounts from about $1100^{o}C$ onwards.

Qualitatively, mica is termed as difficult to fuse but data on melting point, heat of fusion, heat of vaporization and heat of sublimation, etc., could not be located.

d. Optical Properties [53]:

1. Pure musovite is transparent and colorless. Impurities discolor the material.
2. Most micas are biaxial, levorotary and moderately birefringent.
3. Some micas display asterism.
4. The refractive index along the optical axes are $\mu_m = 1.593$ and $\mu_g = 1.597$ for the D line of sodium light.

Commercial Description, Availability and Uses of Mica:

The common form of Indian mica is graded as No. 5, 1st and 2nd quality block form and could be in sheets as large as 24" x 30". Other grades describe flakes and powder. Argentina mica has eight grades from No. 6, in sheets of 1 sq.in. to 3 sq.in., to AA or 'Special', in sheets of 48 sq.in. or more.

Commercial mica sheets are about 0.030" thick. Block mica is designated as "not less than 0.007" thick and minimum of 1 square inch. Mica splittings could be from 0.0012" to 0.004" thick and 1" to 2" in diameter.

High quality sheet mica is used as a dielectric in capacitors. Electric mica is of a lower quality and is employed as an insulator in hot plates, irons, etc. Asbestos sheets are fast superseding mica, however.

Scrap mica is ground down and used in paints, rubber, plastic, etc.

Micanite is a built-up mica, made by bonding thin layers of splittings with shellac or glyptal binders and drying under pressure. This is an insulator used in motor commutators.

Reconstituted mica is made of flakes which are formed into sheets by paper-making methods, which are then submitted to a high pressure and temperature to unite the flakes by recrystallization. The absence of hydroxyl ions gives this synthetic mica a higher heat resistance.

An extensive list of agencies who supply sheet mica is available [59] out of which the addresses of three are:

a. Industrial Mica
P.O. Box 268,
Englewood, N.J. 07631

b. Mica Craft
51 Liberty Street
Newark, N.J. 07102

c. Polymica and Insulation Co. Inc.
34-54-T Arbor St.
Hartford, Conn. 06106

H. CONCLUDING REMARKS

In this report, we have examined the various aspects of liquid pool formation, evaporation, ignition, burning and extinguishment in such a detail as to identify the role played by gravity. Upon this examination, we delineated those areas of pool behavior which would uniquely benefit from study in the Spacelab and developed a conceptual design of a versatile experiment. Some preliminary expositions into the questions of feasibility of this experiment are also reported. To resolve several feasibility issues by use of ground-based research and to develop the experiment design for installation in the Spacelab are the immediate future steps.

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