N89-20311

ABSTRACT

Particle Cloud Combustion In Reduced Gravity

by

A. L. Berlad

Dept. of Applied Mechanics and Engineering Science
University of California, San Diego
La Jolla, California 92093

Study of flame propagation and extinction for premixed flames has occupied a position of central interest in combustion science. Despite the substantial body of experimental and theoretical work achieved to date, experiments aimed at determining these properties for quiescent premixed particle clouds in a gaseous oxidizer suffer from a number of serious deficiencies. The experiments cannot be conducted in normal gravity because:

(1) gravity causes the sedimentation of particles of significant size, thereby rendering spatial and temporal uniformity of a quiescent reactive particle cloud impossible.

(2) mixing-induced turbulence and secondary flows used to suppress sedimentation and to create uniform particle clouds imply ill-defined transport properties. Such mixtures sustain the problems of item (1), above, when particle-uniformity-promoting stirring ceases.

(3) fuel-oxidizer ratio fluxes through freely propagating flame fronts are functions of the gravity vector, and

(4) gravity induced natural convection processes modify the underlying flame propagation and extinction phenomena.

The principal objectives of this microgravity experimental program are to obtain flame propagation rate and flame extinction limit data for several important premixed, quiescent particle cloud combustion systems under near zero-gravity conditions. The data resulting from these experiments are needed for utilization with currently available and tractable flame propagation and extinction theory. These data are also expected to provide new standards for the evaluation of fire hazards in particle suspensions in both Earth-based and Space-based applications. Both terrestrial and Space-based fire safety criteria require the identification of the critical concentrations of particulate fuels and inerts at the flame extinction conditions.

The Particle Cloud Combustion Experiment (PCCE) employs a circular array of flame tubes. Within each flame tube, a uniform quiescent cloud of particles (of selected stoichiometry) is to be suspended in near zero-gravity. The successful establishment of these initial conditions is essential to the successful observation of well-defined flame propagation and extinction processes. Cloud preparation and flame observation elements include: acoustic sources to promote macromixing; arrays of weak α-particle sources to prevent significant par-

ticle-particle agglomeration and particle-wall attachment; arrays of optical sources and detectors to measure particle cloud concentrations and flame propagation rates; igniters, photographic recording of flame propagation and extinction phenomena, and associated electronic control and data acquisition and storage devices. Once a suitably uniform and quiescent particle cloud is established in a flame tube, ignition, flame propagation and extinction characteristics are examined through use of photographic and other optical means.

Fuel particulates to be studied in the PCCE include lycopodium, coal, cellulose, and a number of inerts. Lean flammability limit determination is particularly important and is needed for both fundamental and applied purposes. The long mixing and combustion times for lean flammability limit studies are expected to require STS experimentation. Flame propagation studies of fuel-rich mixtures involve shorter mixing and combustion times and selected data of this kind may be obtained through use of ground-based facilities (e.g., flame propagation studies in airplane-established Keplerian trajectories).

Completed and ongoing studies support the PCCE effort. These have been performed in various ground-based facilities and include studies of: (1) premixed, stabilized lycopodium-air flames under conditions of near zero gravity as well as upward (g=+1) and downward (g=-1) flame propagation in normal gravity.

(2) particle cloud mixing methods, with provision for inhibition of particle-particle and particle-wall attachment processes.

(3) effects of vaporization-pyrolysis endothermicities and radiation-conduction transport on flame propagation and extinction characteristics.

Observations and deductions include the following: Stabilized, upward flame propagation (g=+1) is much more stable than downward flame propagation (g=-1). Omnidirectional radiative losses from lycopodium-air flames are much larger than conductive losses to the cold boundary. Flame structures for the three cases (g=0, ± 1) are substantially different. Additionally, acoustic mixing methods, combined with distributed α-particle sources have been uniquely successful in assuring that planned and optically characterized suspensions of particulates (in air) are meaningful. The success of these methods is essential for the proper establishment of a quiescent cloud in any given flame tube of the PCCE apparatus.

1. INTRODUCTION AND BACKGROUND

The characteristic flame propagation and flame extinction processes sustained by a uniformly premixed, quiescent fuel and oxidizer are of central interest in the fundamental and applied combustion sciences. Treatises on Fire Safety for gaseous systems feature experimental data describing the range of fuel-oxidizer ratios within which quasi-steady flame propagation can (or cannot) occur (Ref. 1). Corresponding combustion theory attempts to describe the flame's structure, its propagation speed, the extinction process, and other conditions that may limit quasi-steady flame propagation (2). Fundamental to this experimental and theoretical correspondence is the requirement that the unburned combustible medium is initially quasi-steady. For premixed combustible gaseous systems, initial spatial and temporal uniformity of a combustible system's chemical, transport, and thermophysical properties is easily achieved, prior to combustion experimentation. At normal gravitational conditions, the corresponding quasi-steady requirements for particulate fuel clouds is not achieved (3-6). Accordingly, the extensive body of experimental observations characteristic for premixed gaseous combustion (autoignition, ignition, laminar flame propagation, extinction, oscillatory oxidation, and other phenomena) is not matched by a corresponding body of combustion data characteristic for initially quasi-steady premixed particle clouds. At normal gravitational conditions, uniform, quiescent particle clouds cannot be established because:

(1) Gravity causes the sedimentation of particles of significant size, thereby rendering spatial and temporal uniformity of a quiescent fuel particle cloud impossible.

(2) Mixing-induced turbulence and secondary flows, used to suppress sedimentation and to create uniform particle clouds, imply ill-defined transport properties. Such mixtures sustain the problems of item (1) when particle-uniformity-promoting stirring ceases.

(3) Fuel-oxidizer ratio fluxes through freely propagating flame fronts are functions of the gravity vector.

The systematic experimental study of freely propagating flames through clouds of uniform, quiescent particulates is thus not feasible at normal gravity. However, premixed particle cloud flames have been stabilized on burners and studied at normal gravity.

Premixed coal-air flames have been stabilized on burners and their properties in the upwards propagation mode observed (7-9) at normal gravity. More recent experiments with burner-stabilized premixed lycopodium-air flames have been carried out in upwards propagation ($g = +1$), in downwards propagation ($g = -1$) and in reduced gravity ($g \simeq 0$). These latter studies (10,11) show that the stability and structures of these three flame propagation modes are substantially different. Premixed, stabilized particle cloud flame characteristics are related to those for freely propagating flames. However, burner-stabilized flame propagation rates and existence limits depend importantly on experimentally predetermined flow and burner conditions. Freely propagating flames (sustained by initially quiescent, uniform combustible media) display characteristic flame speeds and existence limits. Thus, it is the limiting, fuel-lean concentrations of freely propagating flames that are associated with the "lean flammability limit" for any given premixed fuel-oxidizer system. (1,2,12).

In the neighborhood of lean flammability limit fuel concentrations, normal gravity buoyancy effects on the slowly propagating flame structures are most pronounced. This is widely observed for premixed, freely propagating gaseous flames (1,12-14). It is observed for both stabilized and for freely propagating (4) particle cloud flames. Oddly enough, stabilized premixed gaseous flame studies analogous to those done recently (at $g = 0, \pm 1$) for particle clouds (10,11) have not been reported. Nevertheless, the experimental combustion literature shows that normal gravity buoyancy effects are most pronounced for the cases of near lean limit fuel concentrations. This is observed for premixed gaseous systems as well as for premixed particle cloud flames. It is observed for burner stabilized as well as for freely propagating flame systems.

Fundamental flame theory seeks to describe flame structure, flame propagation speeds, and flame existence limits (2,15-21). Currently tractable fundamental flame theory generally neglects gravitational (and other body force) effects of flame propagation characteristics (2,15-21). Heavily truncated phenomenological theories are generally used to characterize experimental flame propagation and extinction data where buoyancy plays a substantial role (12,13).

For premixed flame systems in general, the available $g \simeq 0$ theoretical formulations do not correspond satisfactorily to the available $g = \pm 1$ experimental observations, for freely propagating flames sustained by near-lean-limit fuel concentrations. For premixed particle cloud flames, sedimentation as well as buoyancy effects further degrade the correspondence between $g = \pm 1$ experimentation and $g \simeq 0$ theory.

The studies described in this paper are concerned with understanding the experimental behavior of particle cloud flame propagation and extinction processes under reduced gravity conditions where sedimentation and buoyancy effects do not significantly modify the underlying $g \simeq$ zero combustion processes. Such experimental observations are associated with initially quasi-steady, defined combustible particle clouds. These experimental data may then be utilized, together with existing fundamental flame theory, to help provide an understanding of the underlying $g \simeq 0$ flame processes of interest. Understanding of these underlying $g \simeq 0$ flame propagation and extinction characteristics are needed as a basis for understanding general particle-cloud flame processes, including the effects of gravitational, transport, compositional, and other combustion parameters.

2. GRAVITATIONAL EFFECTS AND THE PARTICLE CLOUD COMBUSTION EXPERIMENT

The principal objective of the Particle Cloud Combustion Experiment (PCCE) is to provide flame propagation rate and extinction condition data for quiescent uniform fuel particle clouds. At normal gravity, particle sedimentation processes compromise our ability to properly prepare a combustible system for meaningful study of freely propagating flames and their limiting conditions for propagation. During combustion experimentation, buoyancy effects (as well as continuing sedimentation processes) further compromise our ability to understand the experimental observations (3-6,10-14). An examination of the character and magnitude of these gravitational effects is useful. Normal gravity difficulties as well as the unique research opportunities afforded by reduced gravity are thereby characterized.

Particles of initial interest in this investigation have maximum densities (∿1.35) and maximum diameters (∿70μm) such that their settling speeds, at normal gravity, are in the Stokes regime. In this regime, the particle settling speed (in air) is given by

$$V_t = gr^2 \left[\frac{2}{9}\right]\left[\rho_p/\mu_g\right] \qquad (1)$$

where g is the acceleration due to gravity, r the particle diameter, ρ_p the particle density and μ_g the gas (air) viscosity. The first fuel particulate under study is the lycopodium spore, which has a mean diameter of about 27μm and a density very close to unity. Some properties of lycopodium are given in Table (1). Pocahontas coal particles (also to be studied) have a density that is about one third higher than that for lycopodium.

At normal gravity, lycopodium has a settling speed of about 3 cm/sec. If one attempts to mix lycopodium with air in a 5 cm. i.d. tube (classically, the inside diameter of a flame tube selected for flammability limit measurements) (1), to create a uniformly mixed cloud, the quiescent uniformity criterion for the combustion experiment cannot be met. Mixing-induced turbulence and secondary flows must be allowed to decay, prior to flame initiation (ignition occurs at one end of a 75 cm. long flame tube). The unburned combustible medium must display time invariant properties, prior to arrival of the flame front. Near fuel-lean flammability limits (the minimum fuel-air ratio capable of supporting quasi-steady flame propagation), flame speeds of the order of 10 cm/sec., or less, may be characteristic. Any reasonable criterion of both quiescence and uniformity

Lycopodium Spore Diameter

Major Axis : 30 $\mu m \pm$ 1.5 μm

Minor Axis : 25 $\mu m \pm$ 1.5 μm

Stoichiometric Ratio : 124 mg / liter

Combustion Enthalpy : 30.25 Mj / Kg

Density

Single Particle : 1015 Kg / m^3
Bulk Density : 400 Kg / m^3

Adiabatic Flame Temperature : 1975 °K

Analyais

Carbon : 65.8 %
Oxygen : 21.9 %
Hydrogen : 9.6 %
Nitrogen : 1.2 %
Sulphur : 0.2 %

Table I : Some Properties of Lycopodium Particles.

cannot be met. Post-mixing periods needed to achieve quiescence have been estimated to be of the order of 10 seconds, for energetic acoustically-induced mixing processes. Minimum time requirements for maintenance of a quiescent cloud, prior to flame front arrival, is of the order of 10 seconds, or more. If the cloud of vigorously mixed particles is to be allowed to settle (or drift) by no more than 10 percent of a tube diameter during a total experimental time of some 50 seconds, utilization of equation (1) implies the need for a reduced gravity environment (g*) of about $10^{-3} g_0$ to $5 \times 10^{-4} g_0$ where g_0 is the acceleration due to normal gravity. It is clear that mixing of lycopodium (to uniformity) in reduced gravity is an easier and shorter task than mixing attempts at g_0. This requirement for a reduced gravity environment is one of three shown in Table (2).

Another normal gravity obstacle to achievement of the experimental objectives relates to the effective number of particulates, consumed by a flame front which propagates upwards ($g_0 = +1$) or downwards ($g_0 = -1$) at normal gravity. Even if the particle cloud were uniform and quiescent (at normal gravity) the particle number swept out per unit time by a given quasi-steady flame front (propagating upwards or downwards) is different. The effective concentration of such a flame front is given by (4)

$$c^* \simeq c_0 \left[1 \pm \frac{V_t}{U_f} \right] \qquad (2)$$

where c* is the effective concentration, c_0 the actual concentration, V_t the settling speed, and U_f the flame speed. The positive sign corresponds to upwards propagation and the negative sign corresponds to downwards propagation. The upwards propagating front enjoys an enriched fuel concentration. The downwards propagating front experiences a depleted fuel concentration. This effect is particularly troublesome for large dense particles and for the very slow flames anticipated in the neighborhood of flammability limits. For example, a lycopodium-air flame speed of 3 cm/sec., observed in upwards propagation would correspond to an enriched particle concentration of $c^*_+ \sim 2c_0$. The same flame speed in downwards propagation is a physical impossibility. In the latter case $c^*_- \sim 0$. Here again, use of the reduced gravity environment allows the imposition of effective limits on the difference between c* and c_0, regardless of the direction of the gravity vector. If we require that $(V_t/U_f) \leq 0.02$, we find that the required range of reduced gravity conditions is of the order $g_* \approx 10^{-2} g_0 - 10^{-3} g_0$. This requirement for a reduced gravity environment is one of three shown in Table (2).

Another normal gravity obstacle to achievement of an important experimental objective relates to the effects of buoyancy in flames. These effects are well-known for purely gaseous flames (1,12-14) and are also observed for particle-cloud flames. Lovachev (12) has discussed the relation between a characteristic time and other parameters

1 Reaction zone's effective concentration is to be kept close to actual: where $C^* = C_0 (1 \pm V_t / U_f)$ and $V_t / U_f \leq 0.02$	$g^* \approx 10^{-2} g_0 - 10^{-3} g_0$
2 The dispersed cloud is to be restricted to small drift during a 50 second combustion process, where $\delta \approx 0.5$ cm. and $\rho = 1.0$ gm/cc	$g^* \approx 10^{-3} g_0 - 5.0 \times 10^{-4} g_0$
3 Buoyancy-induced flows due to post-reaction zone products are to be inhibited during the combustion process. $[t_s^3 g^2 / \nu] \approx$ constant Ref. : Lovachev, Comb. & Flame, 20, 259 (1973)	$g^* \approx 10^{-2} g_0$

Table 2: Experimentally Required g-Values.

for hot combustion product buoyancy effects on premixed flame propagation rates. His studies lead to the relation

$$\frac{t_k^3 g^2}{\nu} \approx \text{constant} \qquad (3)$$

where t_k is the time (after ignition) necessary for the development of significant buoyancy effects on flame propagation, g the gravitational constant, and ν the kinematic viscosity. The characteristic group of equation (3) was developed through observation of hot product buoyancy effects of premixed gaseous flames as a function of pressure, at normal gravity. Lovachev finds that an ambient pressure of one-tenth atmospheric is adequate for virtual suppression of this buoyancy effect. Based on the Lovachev data (12) and a conservative estimate of some 50 sec.-100 sec. needed for a particle-cloud combustion experiment at reduced gravity, it follows that a value of $g^* \approx 10^{-2} g_0$ is needed to achieve about the same buoyancy-suppression effects for particle-cloud flames at reduced gravity. This requirement for a reduced gravity environment is one of three shown in Table (2).

Finally, we note a flame reaction zone buoyancy effect whose significance has not yet been evaluated. It has been noted (14) that the reaction zone ratio of the gravitational to pressure terms for a flat freely propagating gaseous flame is given by the ratio

$$\frac{(\rho_1 + \rho_2)\, gh}{2\,(p_2 - p_1)} = \sigma \qquad (4)$$

where ρ_1 and ρ_2 are the respective densities downstream and upstream of the reaction zone, h the reaction zone depth, and $(p_2 - p_1)$ is the pressure drop across the reaction zone. The reaction zone thickness varies inversely with flame speed. Near the flammability limits, it is expected that (h) may become a relatively large value. Inasmuch as the near-lean-limit flame speed for experiments of interest (in this study) are not known, the value of σ is not known and its possible significance cannot be fully assessed. However, the observations (12) that led to equation (3) suggest that the reaction zone buoyancy effects are no more significant than the combustion product buoyancy effects, for the range of stoichiometries studied and reported in reference (12). A plot of (σ) versus equivalence ratio for Methane-air flames in shown in reference 14.

Based on the above cited considerations, it is concluded that gravitational conditions of the order of $g^* = 10^{-3} g_0$ are adequate to fulfill virtually all requirements for suppression of sedimentation and buoyancy effects.

3. PARTICLE CLOUD COMBUSTION EXPERIMENTS

The principal objectives of the microgravity experimental program are to obtain flame property and flame extinction limit data for a variety of premixed, quiescent two-phase combustion systems under near zero gravity conditions. In a previous section, the essential need for reduced gravity conditions was discussed. In subsequent parts of this report, ongoing complementary experimental and theoretical studies are discussed. We here discuss the principal features of these particle cloud combustion experiments as well as the needed use of NASA's reduced gravity facilities.

It is anticipated that several of the NASA reduced gravity facilities must be employed to help gather the scientific data required. The study of extinction phenomena and flame propagation rates of fuel-lean systems requires both the long reduced gravity time and the low values of the gravity levels offered by STS. Near the lean flammability limits, flame speeds are at their slowest (perhaps significantly less than 10 cm./sec) and the rate of change of flame speed with fuel concentration is at its highest (9-14). Accordingly, mixing times and flame propagation times associated with a 75 cm. long flame tube are expected to require STS conditions. However, the higher flame propagation rates of fuel-rich mixtures (which could be studied in STS) may also permit the collection of needed scientific data in ground-based facilities (e.g., airplane flights in Keplerian trajectories).

Experiments to be studied emphasize the following features:

(1) Establishment and certification of an adequately quiescent, uniform particle cloud in a 5 cm. i.d. tube, for purposes of measuring the characteristic flame propagation rates and extinction conditions.

(2) Determination of the characteristic lean extinction limits for such systems requires a series of experiments, each corresponding to a different stoichiometry.

(3) Several prototypical particulates are to be studied. The first of these is to be lycopodium. Particle size uniformity, batch reproducibility, low ash content, and compositional correspondence to coals of interest make this particle type our first choice for study. Subsequent studies of coal particulate clouds and of cellulose particulates are planned.

(4) For any experiment conducted, flame initiation, flame extinction, and end gas combustion sequences are time dependent processes. Photographic and localized flame detectors are needed to establish these properties as well as spatial regimes of quasi-steady flame propagation. These also establish flame structure properties. The same localized detector arrays are to be used to help characterize particle

C-2

cloud uniformity prior to ignition. Information on unsteady, multidimensional features of the phenomena is to be recorded photographically.

Detailed preliminary design information regarding these experiments is given in references 4,22,23. Nevertheless, it is important to identify here the experiments that are considered to be primary. The STS experiments are to be supported importantly by complementary ground-based studies. Both classes of studies involve the sequential study of varied concentrations of lycopodium suspended in an oxidizing gaseous atmosphere (air).

The study of low burning velocities (less than 10 cm/seconds) and the rapid changes in burning velocity in the neighborhood of lean flammability limits requires the long microgravity conditions of STS. For a range of fuel-rich flames, burning velocities are high, probably on the order of or greater than 15 cm/second. These flame speeds are relatively insensitive to stoichiometry variations, and extinction conditions are not approached. For such flames, ground-based facilities may be advantageously employed. For these latter studies, combustion times are less than 5 seconds which, under ideal aircraft microgravity conditions, then allows some 10 to 15 seconds for completion of a mixing process. Aircraft-based experiments also permit extensive involvement of an expert combustion scientist. The anticipated simple dependence of rich mixture burning velocity on stoichiometry permits the experimental study of these relationships with only a small number of experiments. The experimental test matrix for lean and near stoichiometric mixture experiments is shown in Table (3). The experimental test matrix for richer mixture experiments is shown in Table (4). The "Equivalence Ratio", shown in Tables 3 and 4, is a measure of the suspended particle concentration and is defined as the actual fuel-air mass ratio divided by the stoichiometric fuel-air mass ratio. It is anticipated that the experimental test matrix displayed on Table 3 requires the use of the STS. However, the experimental test matrix of Table 4 may be conducted in ground-based facilities, if acceptable cloud uniformity can be achieved in a short time period of microgravity.

The matrices of target equivalence ratios were selected on the basis of studies to date and the requirement that the equivalence ratio of the extinction limit be determined to an accuracy of about five percent.

It appears certain that these will lead to quasi-steady flame propagation. Although the lean extinction limit is not well known, it is expected that the lean flammability will be encountered for $\Phi < 1.0$ but above $\Phi \sim 0.5$. Accordingly, for lean mixture studies, we would choose to give first priority to the cloud stoichiometries shown in Table. 3.

In subsequent lean mixture experiments, it is expected that

Particle Type	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8
• Lycopodium	1.3	1.2	1.1	1.0	0.92	0.84	0.78	0.72
** Lycopodium Plus Inert Particles	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
• 25 μm Pocahontas Coal	2.0	1.8	1.6	1.4	1.2	1.0	0.85	0.75
* 40 μm Pocahontas Coal	2.4	2.0	1.6	1.4	1.2	1.0	0.85	0.75
* 55 μm Pocahontas Coal	2.8	2.4	2.0	1.6	1.4	1.2	1.00	0.90
** 25 μm Pocahontas Plus Inert Particles	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
• 25 μm Cellulose	2.0	1.8	1.6	1.4	1.2	1.0	0.85	0.75

Table (3) : Experimental Test Matrix For PCCE Studies of Lean and Near-Stoichiometric Mixtures.

*   Eight experiments are anticipated for each particle type. Each of these experiments is for a different stoichiometry.

**   Two differnt fuel-to-inert mass ratios are to be investigated for each stoichiometry and fuel-to-inert mass ratios will be selected on the basis of results of earlier inert-free studies.

Particle Type	ϕ_A	ϕ_B	ϕ_C	ϕ_D	ϕ_E	ϕ_F
Lycopodium	1.3	2.0	3.0	4.0	5.0	6.0
Lycopodium Plus Inert Particles	TBD	TBD	TBD	TBD	TBD	TBD
25 μm Pocahontas Coal	2.0	3.2	4.0	5.0	6.0	7.0
40 μm Pocahontas Coal	2.4	3.2	4.0	5.0	6.0	7.0
55 μm Pocahontas Coal	2.8	3.2	4.0	5.0	6.0	7.0
25 μm Pocahontas Plus Inert Particles	TBD	TBD	TBD	TBD	TBD	TBD
25 μm Cellulose	2.0	3.0	4.0	5.0	6.0	7.0

Table (4) : Experimental Test Matrix For PCCE Studies of Rich Mixtures other particulate species (e.g., coal, cellulose) and larger particle sizes will be studied. Nevertheless, it is expected that a single sequence of experiments will be sufficient to determine flame propagation and extinction characteristics for any particle cloud type to accuracies of five percent or better.

Should subsequent flight opportunities permit, particle mixtures and particle size mixtures would be proposed for similar studies of flame propagation and extinction conditions. The roles of inert particulate constituents are of special fundamental interest in questions of industrial safety and dust flammability (Refs. 6,31).

An experimental test matrix for the proposed 56 STS tests is given in Table 3. Although it has been assumed here that there will be 8 tests per flight, design considerations may prescribe a smaller/larger number. Figures (1) and (2) give the apparatus schematics.

The rich mixture experiments proposed for aircraft tests (shown in Table 4) will permit the experimental study to determine kinetics of pyrolysis effects on flame propagation theory and to determine burning velocity behavior over a wide equivalence ratio range.

A number of generic apparatus, probe, fuel, data recorder and mission specialist support features are required by the experiments planned. Detailed arguments supporting the specification of these generic elements of the experimental program are given in the science requirements (Reference 24). The major science requirements and their possible implications regarding engineering design are discussed in the following subsections:

(1) A flame tube of 0.05 ± 0.002 meter i.d. is selected, by definition and by conventional practice, to help define flame propagation and extinction conditions for any quiescent fuel-air mixture. The tube must be long enough to assure observable quasi-steady flame propagation (within the extinction limits) and strong enough to safely contain all possible combustion processes. Preliminary experiments indicate that a tube length of about 0.75 ± C.002 meters is suitable. Gold-coated tubes are necessary in order to adequately impose radial boundary conditions. In some cases, the electrically conductive properties of gold-coated tubes may also be necessary to suppress particle-wall adhesion. Aircraft studies of rich mixtures with both gold-coated and uncoated tubes will permit subsequent selection of tube coatings for STS flights.

(2) Test fuel particle types are lycopodium, selected coal, and cellulose. Lycopodium particle clouds are to be studied first.

(3) Particle cloud equivalence ratios are determined by the concentration of suspended particulates, rather than the total num- of particulates within the flame tube. Methods of reducing the

wall surface density of particulates have been identified. Even for extremely small wall saturation effects, wall surface densities must be known in order that suspended particulate concentrations can be determined. During in-flight experimentation, in situ determination of fuel-air equivalence ratio is to be derived from cloud optical attenuation measurements. To achieve adequate accuracy in the determination of flammability limits, a precision of ±5 percent is required in the measurement of particle concentration. In this regard, optical probe source and detector windows may employ special wall saturation suppression techniques. The ±5 percent precision requirement relates both to mean variation observed at any one optical attenuation station and the deviation from the mean, taken for the several optical attenuation measurements over a 10-second time period (during orbital flight).

(4) Preparation of the particle cloud in microgravity requires that particle mixing techniques be employed. Where vigorous acoustic mixing is employed, turbulence and secondary flow decay times are on the order of 10 seconds.

(5) The desired value of pressure for the experiment is $p=1$ atm, to directly relate to normal gravity experiments. Although the combustion processes under investigation do not vary substantially over a small initial pressure range in the neighborhood of $p = 1$ atm, it is important that pressure be constant during the combustion event. A pressure stability of approximately ±0.2 psi/second is needed during the combustion event.

(6) Successful ignition of a quasi-steady flame is best achieved and identified when an energetic igniter (e.g., nitrocellulose) and an oversized ignition section (e.g., 7.5 cm. i.d. x 12 cm. long) are employed.

(7) Ambient temperature conditions should be stable during experimentation. Initial temperature should be 294°K ±6°K with a stability of ±2°K per minute during the experiment. A uniformity of ±4°K over the tube length is required.

(8) Effective gravitational conditions should be small and steady. A g-level environment, of 5×10^{-4}g is desired with a stability of $\pm 1 \times 10^{-4}$g. Higher g-levels up to 5×10^{-2}g can be tolerated in the aircraft experiments. It is recognized that the desired g-level may not be satisfied at all times on the STS. Therefore, for STS experiments, tests should be conducted during "quiet periods", and the synchronized g-level recorded at a frequency of 1 HZ during the entire experiment.

(9) Air composition should be "normal" and "dry" with 79 percent N_2 and 21 percent O_2.

(10) Near-field camera framing rates are to be 100/second in order to achieve sufficient resolution in time. It is desired to have a camera field of view such that the entire flame tube is contained therein. A full view of the tube's length, including

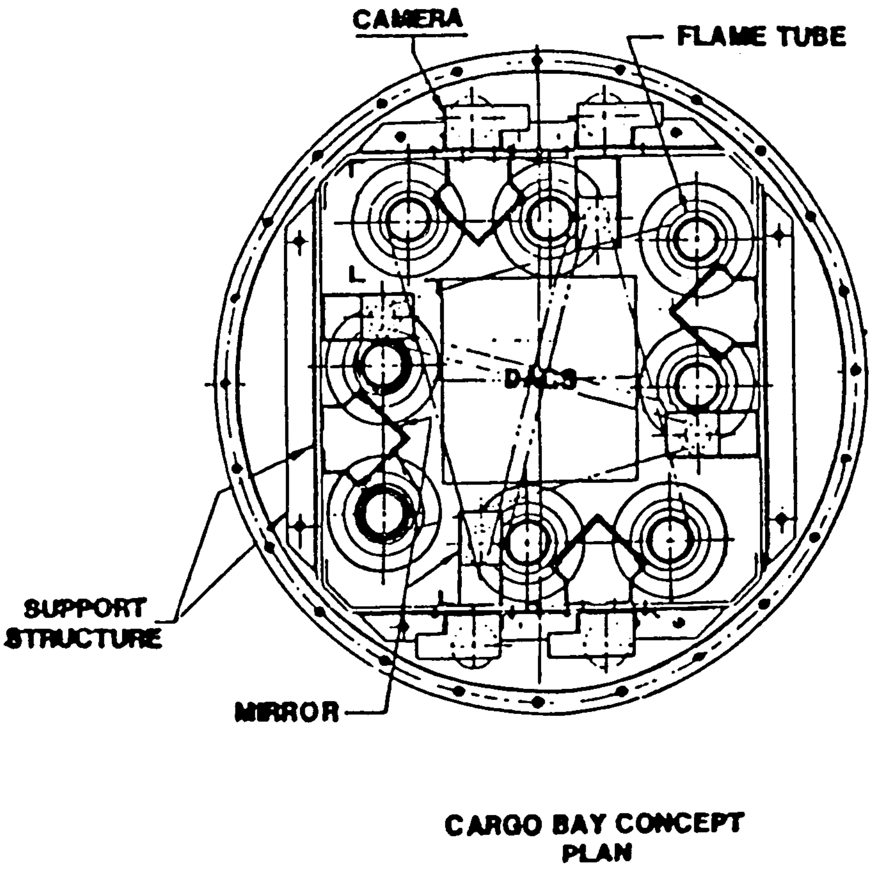


Figure 1: Flame Tube Assembly, Particulate Cloud Combustion Experiment.

ORIGINAL PAGE IS
OF POOR QUALITY

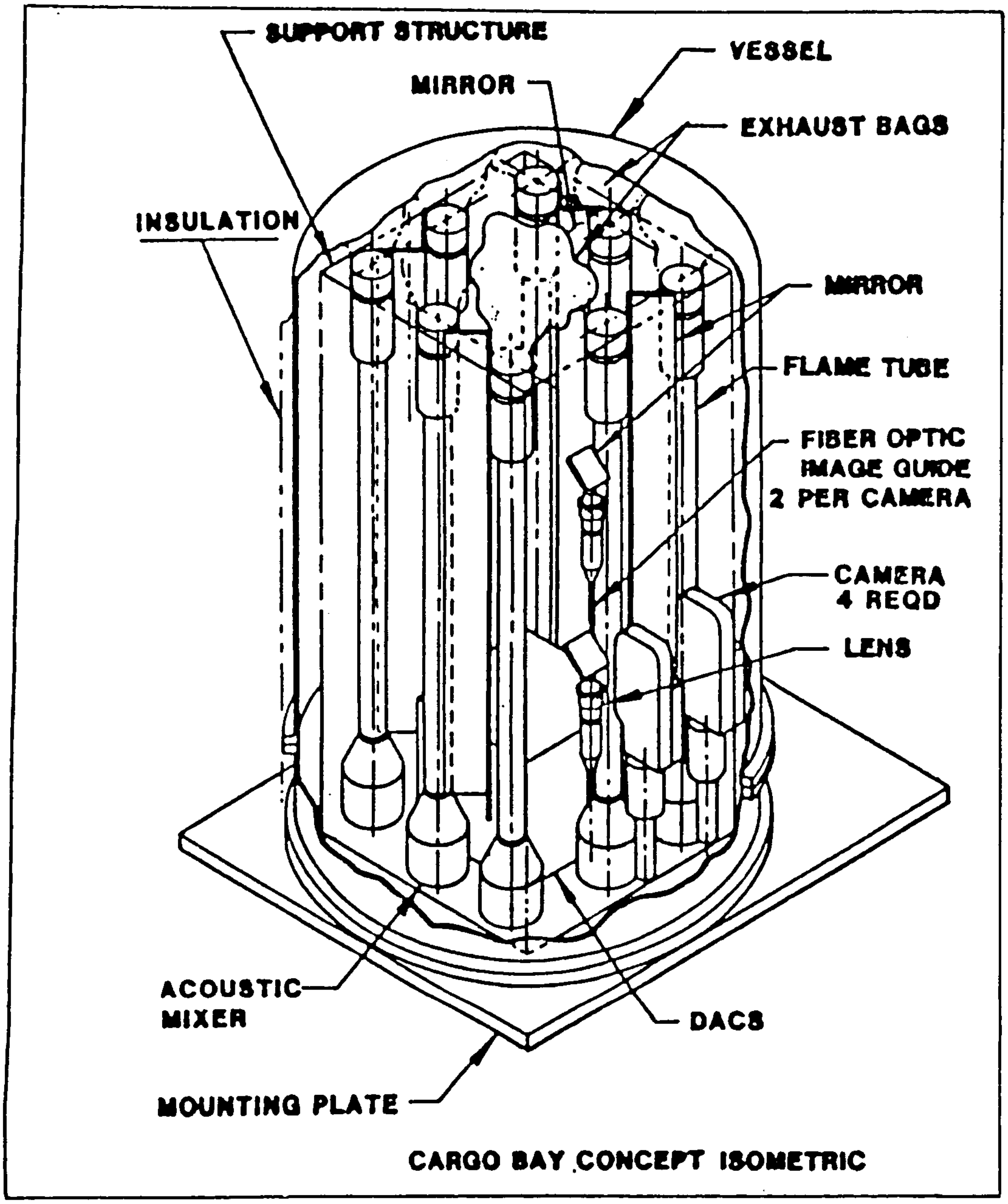


Figure 2: Cargo Bay Isometric, Particulate Cloud Combustion Experiment.

the ignition zone, must be within the field of view in order to adequately establish the steadiness properties of the flame. Film records must be synchronized to 0.005 seconds with the measured data.

(11) Mission specialist involvement, wherever possible, is desired. Three dimensional and time-dependent combustion effects may be observed by the mission specialist directly, and by long focal length motion picture photography (mission specialist operated). In the neighborhood of extinction limits, it is necessary to distinguish an inadequate ignition attempt from an extinguished flame phenomenon. A mission specialist (with minimal training) can provide invaluable help in making these observations. In the absence of a mission specialist, two photographic views of the flame tube, 90 offset (approximately) from each other is required.

The schematics of an individual flame tube assemby as well as an eight flame tube experimental arrangement is shown in Figures (1) and (2). Detailed summaries of the essential experimental apparatus requirements (for both STS experiments and aircraft flights) are given in reference (24).

4. SOME ADDITIONAL CONSIDERATIONS FOR PARTICLE CLOUD COMBUSTION EXPERIMENTS

A combustible system's experimentally-determined flammability limits, quenching limits and pressure limits are not completely independent of one another (1-4, 18-20). Comprehensive theoretical consideration of premixed flame existence limits is complicated by the substantial effects that gravitational conditions may impose. Tractable combustion theory is rarely more than one-dimensional. Free convective flows are generally three-dimensional. Upward (g = +1) flame propagation limits are generally wider than downward (g = -1) propagation limits. Findings to date show that this general combustion limit behavior obtains for both premixed gaseous and premixed particle cloud flames (10). This behavior also obtains for burner-stabilized (10) as well as for freely propagating flames (1-4, 10-14).

Recent studies (10) of burner-stabilized lycopodium-air flames have been carried out under all three conditions of interest, g = 0, ±1. A single, fully self-contained apparatus was used for all three gravitational conditions. The g = 0 data (10,11) were obtained at the NASA-Lewis Research Center 2.2 second drop tower facility. It may be surprising that no similar studies of other g = 0, ±1 stabilized flames have been reported, *either for premixed gaseous systems or for premixed particle cloud systems*. These recent findings (10,11) are derived from a burner apparatus capable of measuring heat transfer rates to the burner lip and capable of thermocouple probing of flame structure. Figure (3) is a schematic of the burner apparatus. Figure (4), (5), and (6) show the measured heat transfer rates from stabilized lycopodium-air flames to the burner lip. Figure (7) shows three flame temperature structures, for the three conditions, g = 0, ±1. The findings of references (10) and (11) for stabilized lycopodium-air flames appear to describe stabilized flame properties expected for both premixed particle cloud flames *as well as for* many premixed gaseous flame systems. These findings include the following:

(1) Omnidirectional heat losses sustained by the upstream flame structure at g = 0 are smaller than those for the other two modes (g = ±1) and results in substantially higher peak temperatures for the g = 0 case.

(2) Omnidirectional heat losses sustained by the upstream flame structure at g = +1 are smaller than those for the g = -1 case. This helps to account for the wider stability limits at g = +1 than are observed at g = -1.

(3) Buoyancy effects move the g = +1 flame closer to the cold boundary (than is the case for g = 0). Buoyancy effects move the g = -1 flame further away from the cold boundary. This helps to account for

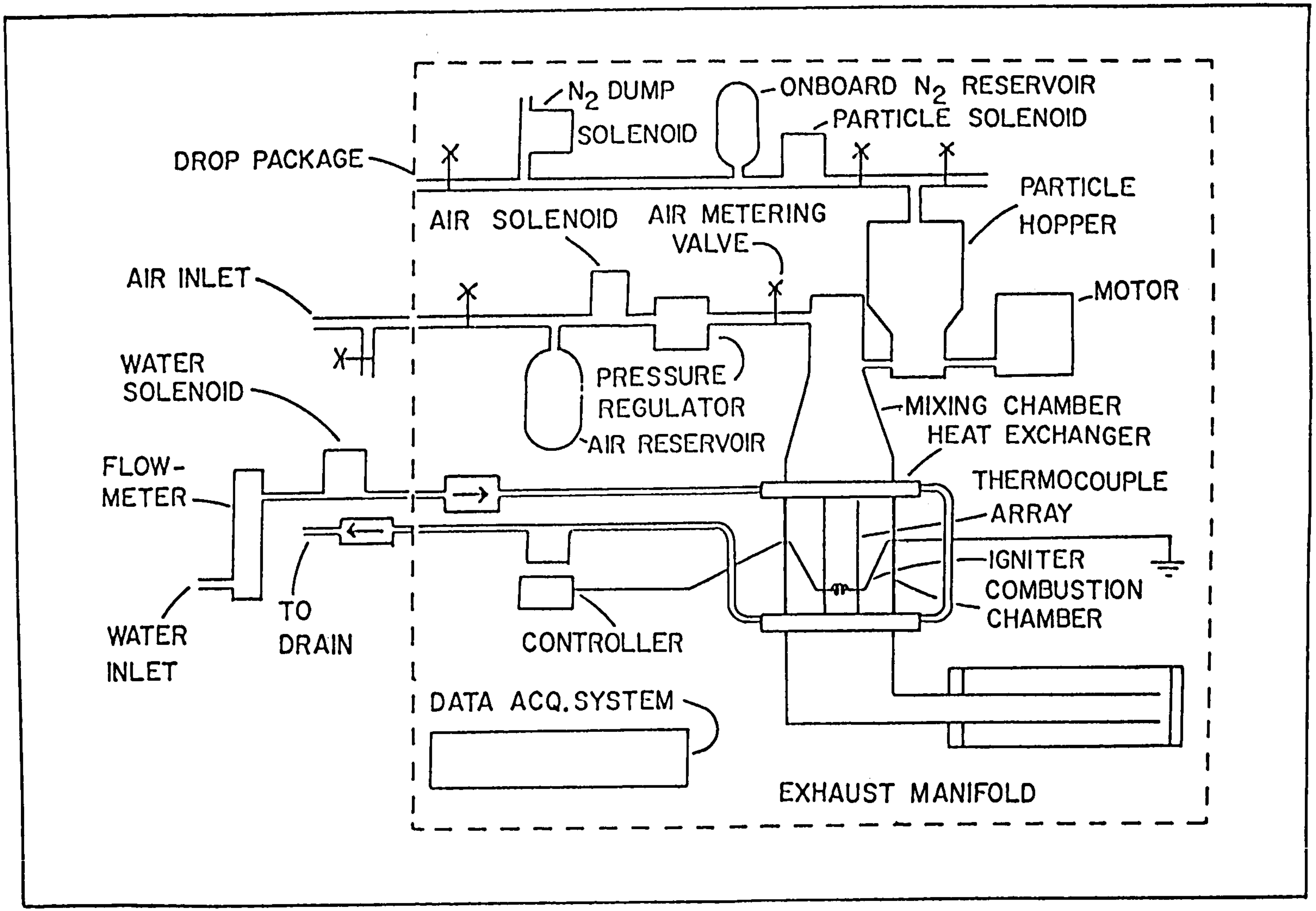


Figure 3: Schematic of the Burner Apparatus Used for the Study of Stabilized Lycopodium-Air Flames at g = 0, ± 1.

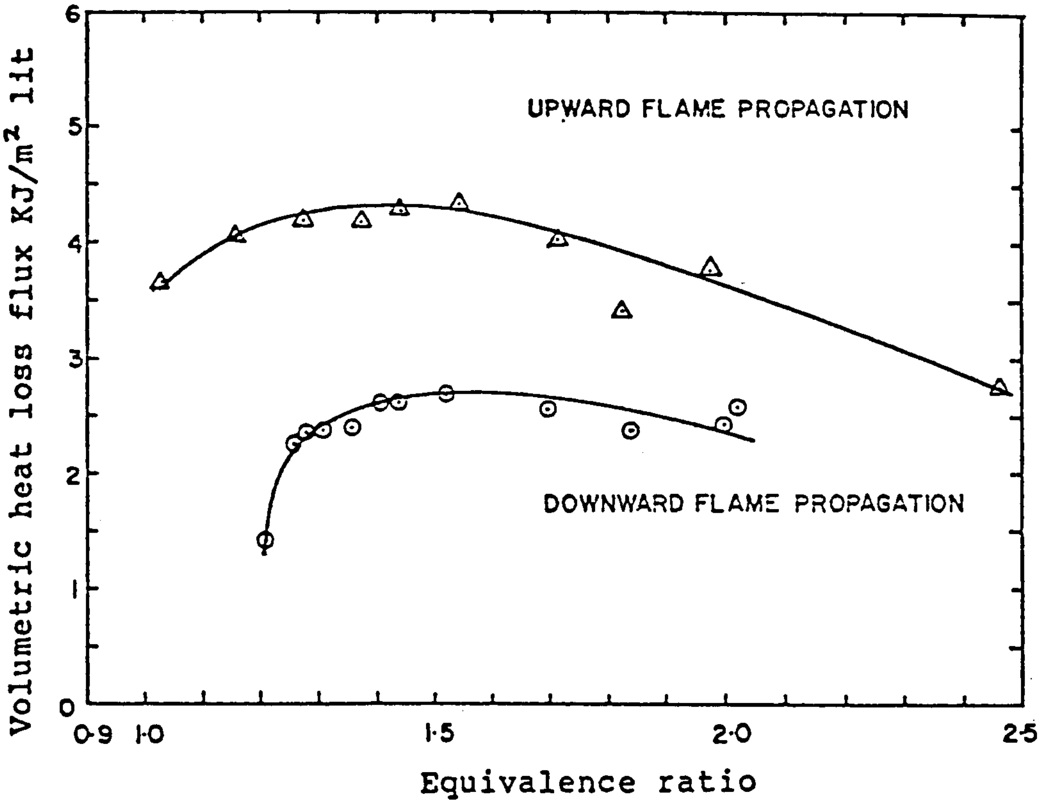


Figure 4: Volumetric Heat Loss Flux for Stabilized Lycopodium-Air Flames for a Flame Velocity of 17.1 cm/sec.

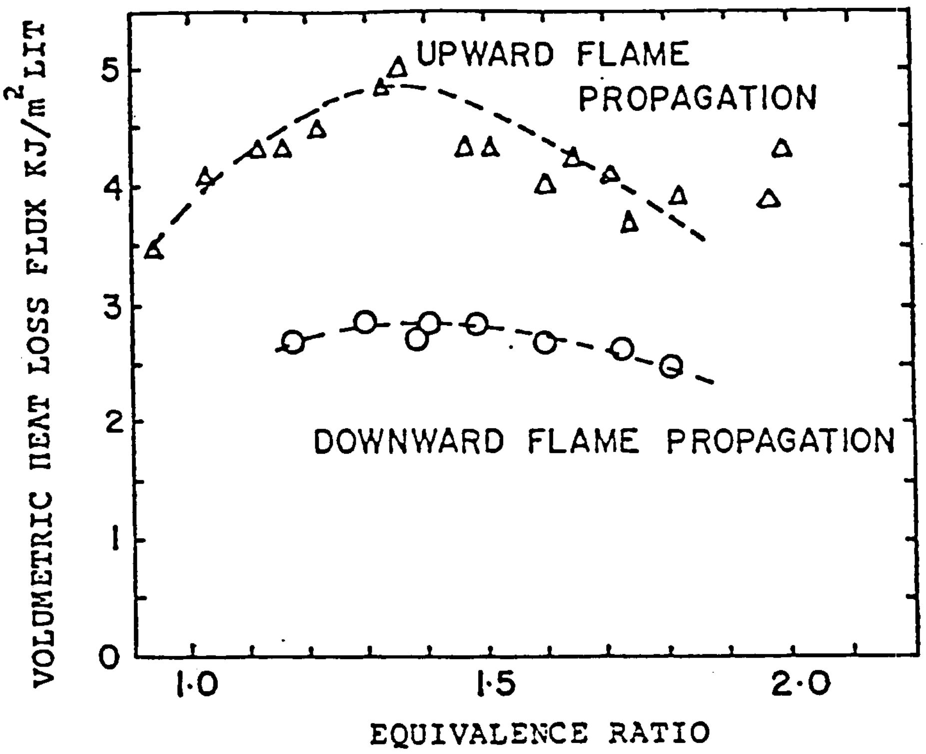


Figure 5: Volumetric Heat Loss Flux for Stabilized Lycopodium-Air Flames for a Flame Velocity of 13.9 cm/sec.

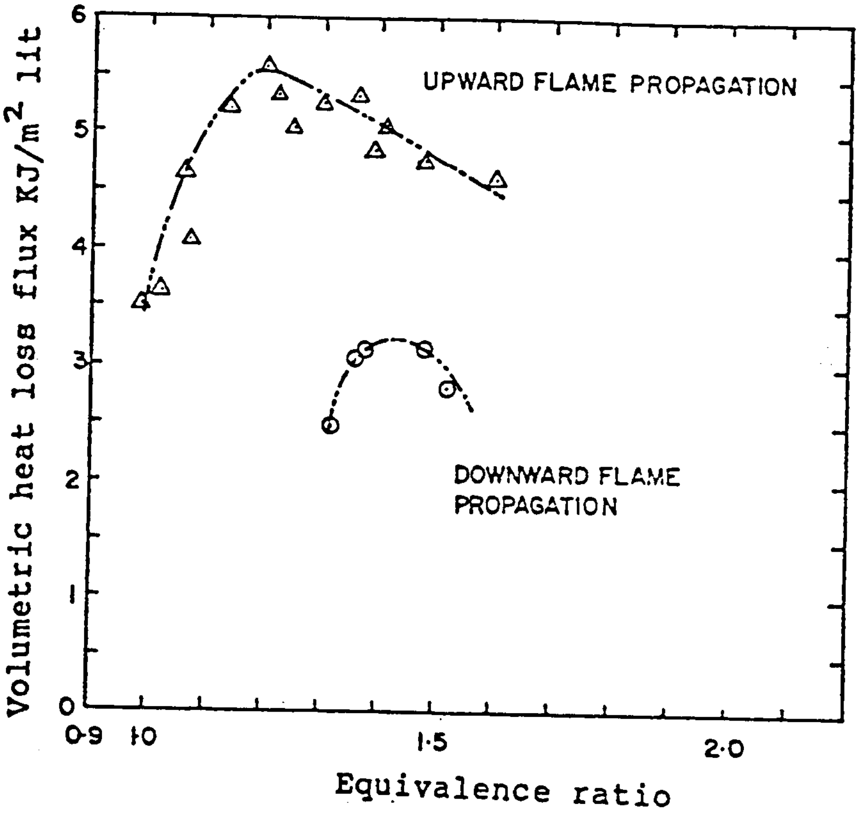


Figure 6: Volumetric Heat Loss Flux for Stabilized Lycopodium-Air Flames for a Flame Velocity of 11.4 cm/sec.

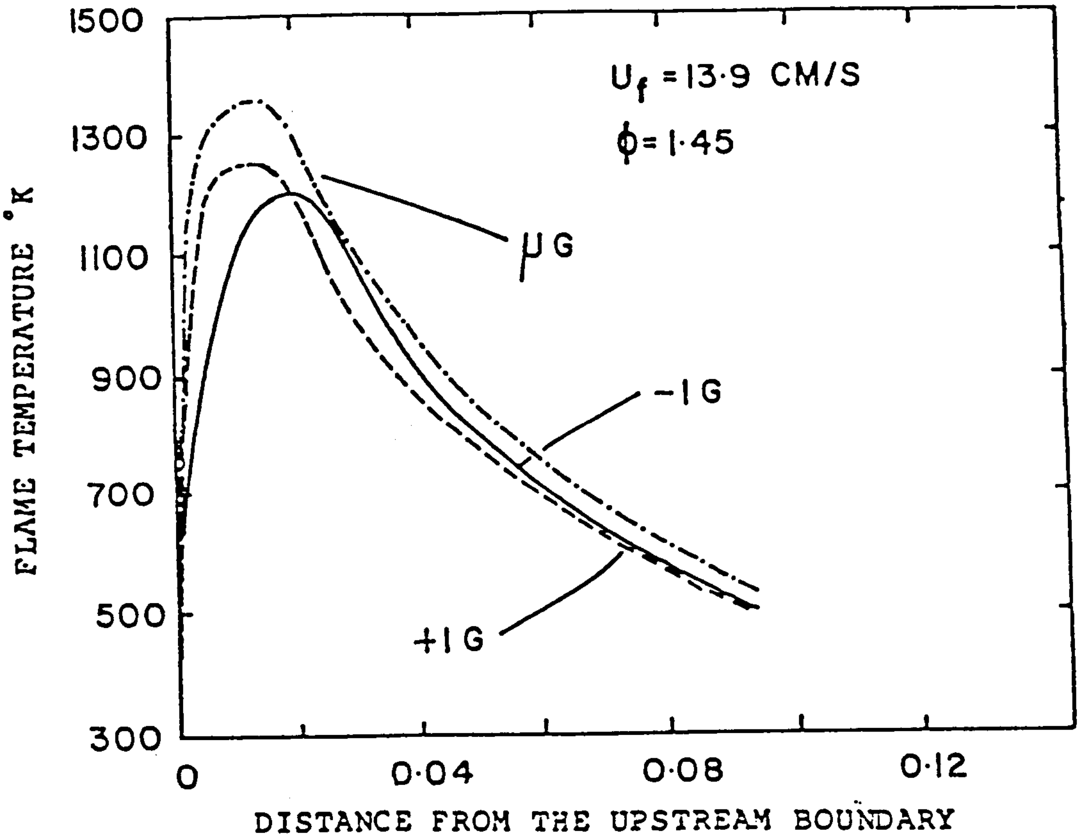


Figure 7: Measured Flame Temperature Profiles for Stabilized Lycopodium-Air Flames for Upward (+1g), Downward (-1g) and Microgravity Flames.

the larger cold boundary heat losses at g = +1 than are observed for g = -1.

(4) From (2) and (3), above, it follows that upstream transverse hear losses at g = -1 are larger than those at g = +1.

(5) From (2) - (4), above, it follows that large omnidirectional heat losses (rather than simply cold boundary heat losses) lead to narrowing of these flame stability limits.

(6) From (1) - (5), above, it follows that flame stability limit theory requires inclusion of omnidirectional heat loss rates. This general observation applies to both purely gaseous flames as well as to particle-cloud flames.

(7) The data show that cold boundary heat losses due to molecular conductive processes are a small fraction of the total heat loss rate to the cold boundary. These data, taken together with the observed temperature structures show that radiative omnidirectional losses are large and that gravitationally induced transverse losses can be significant.

Commonly employed non-adiabatic flame theory (2) (for stabilized flames) is generally one-dimensional and does not take account of gravitational effects. Recent theoretical efforts to consider gravitational effects (25) (in one dimension) and to consider two-dimensional flows (18,26) (without gravitational effects) represent promising starts to more general representations. Flame propagation and extinction theory recently employed for particle cloud combustion generally fails to account for transverse radiative losses (9,19,20, 27).

An interesting aspect of other studies of quasi-steady, burner-stabilized particle cloud flames concerns the effects of particle sedimentation. In general, the experimenter fixes the particle number flux that is to support the steady, stabilized flame. Cold gas particle concentrations are gravitationally influenced and are determined from

$$c_0 = \frac{\dot{n}''}{V_t \pm V_g} \qquad (5)$$

where $\dot{n}''$ is the number flux per unit area, V_t the settling speed, V_g the experimenter-imposed gas speed, and c_0 is the volumetric number concentration of particulates. The positive sign is used where settling velocities and gas velocities are parallel. The gaseous flux is given by

$$\dot{m}_g'' = V_g \cdot \rho_g \qquad (6)$$

and the equivalence ratio (defined to be the fuel/oxidizer mass fluxes divided by the stoichiometric fuel/oxidizer mass flux ratio) is given by

$$\phi = \frac{c_0(V_g \pm V_t)}{\rho_g V_g M_p} \qquad (7)$$

where M_p is a (stoichiometric factor) constant. We may also define ϕ^* as the ratio of fuel to oxidizer mass densities divided by the stoichiometric fuel/oxidizer mass density ratio

$$\phi^* = \frac{c_0}{\rho_g\ M_p} \tag{8}$$

For purely gas phase systems, ϕ and ϕ^* are identical. This is generally not the case for flowing particle cloud systems. The magnitudes and directions of V_t and V_g becomes exceedingly important as experiments are carried out near flammability limits (low values of V_g) and for large particle sizes (high values of V_t). These effects are generally important but not analyzed in the body of data provided by g = -1 burner stabilized studies. Consider, for example, the data derived from the very careful experimental studies reported in ref. (8). Those data (8) are shown in Figure (8) and show flame speed versus particle concentration for burner-stabilized pocahontas coal dust-air flames. Flow was downward, flame propagation upward. The apparatus used (8) was not capable of performing downward flame propagation studies. Left unresolved are the following experimental (and theoretical) issues: What downward propagating flame speeds would be measured, if the apparatus could accomodate the observations? What are the effects of sedimentation, particularly where flame speed values are lowest (and flame stability is marginal)? As one investigates larger and larger particle sizes, a particle size regime is reached where no flame propagation is observable in downward flame propagation $(V_g - V_t) \simeq 0$. To what extent is flame extinction due to buoyancy effects? To what extent is this due to sedimentation effects? To what extent is this due to low volumetric vaporization-pyrolysis rates associated with increased particle size heat transfer effects? Clearly, mixed particle size, burner-stabilized flames are impossible to study at g = -1, where particle settling speeds are a significant fraction of the fundamental flame speeds.

Our forthcoming reduced gravity experiments (starting with Keplerian trajectories in aircraft) are planned (24) to include the use of both infrared reflective wall coatings and in other cases, infrared absorbing flame tube surfaces. Computational methods recently employed for two-dimensional, time-dependent reactive flows (21,28) show great promise for delineating characteristic flame details that are not derivable from steady state flame formulations. Time-dependent computational studies of particle cloud flames involving UCSD-NRL collaborative efforts have been initiated. We note that the constituative equations of particle cloud combustion are generally well known (2,8,9,10,19,20,27). Analytic and/or computational success rests heavily on wise selections of those physicochemical parameters that may significantly influence results -- and neglect of those physicochemical parameters that play insignificant roles. Particle cloud combustion experiments are needed to identify and assess the underlying combustion processes, phenomena, and parameters which are important.

5. PARTICLE CLOUD DISPERSION AND CHARACTERIZATION ISSUES

Fuel particle dispersion in a gas, for purposes of particle cloud combustion experimentation, has been carried out in a number of experiments (5,6,29,30). At normal gravity, these experiments are generally concerned with studies of ignition and explosion in turbulent particle clouds. Time for decay of turbulence and secondary flows is generally longer than the time during which sedimentation compromises the needed particle uniformity.

Joint UCSD-Lewis Research Center studies of mixing methods (to be used in reduced gravity environments) currently emphasize acoustically induced flows to assist in mixing and the establishment of particle cloud uniformity. A problem which appears important to all particle cloud combustion experiments ($g = 0, \pm 1$) concerns the consequences of triboelectrically-induced charge separation processes which derive from vigorous mixing. Charge separation processes sustained by dielectric particles in air can lead to unwanted effects such as the agglomerative growth of particle clusters and the attachment of particulate clusters to combustion chambers walls (22).

UCSD-Lewis Research Center studies have focused on methods of mitigating these unwanted effects. During vigorous mixing (by acoustic or other sources),charge neutralization can be promoted through use of ionizing sources. We have employed arrays of ionizing sources (the active source component is Polonium-210, a weak α-source). Studies to date show that during several minutes of vigorous mixing, particle-particle and particle-wall interactions can be controlled to achieve (22) the following two important objectives:

(1) The vigorously-mixed cloud of particulates remains essentially monomeric.

(2) Particle-wall attachment rates are small. Particle surface densities of the order of 1 particle per square millimeter have been achieved. This corresponds to no more than a one or two percent depletion of the particles to be contained in a flame tube's volume.

Figure (8) is a schematic of the test apparatus used to carry out the aforementioned mixing experiments. Figure (9) shows the arrangement of Polonium strip sources along the inside surfaces of the 15 cm. long by 5 cm. i.d. test chamber. Figure (10) shows the results of particle-particle agglomeration and particle-cluster wall attachment for three different test conditions. Where no ionizing sources were employed, Figure (10-a) shows a wall density of particles that is several orders of magnitude greater than that shown in Figures (10-b) and (11). The experiment that yielded the Figure (10-a) results was

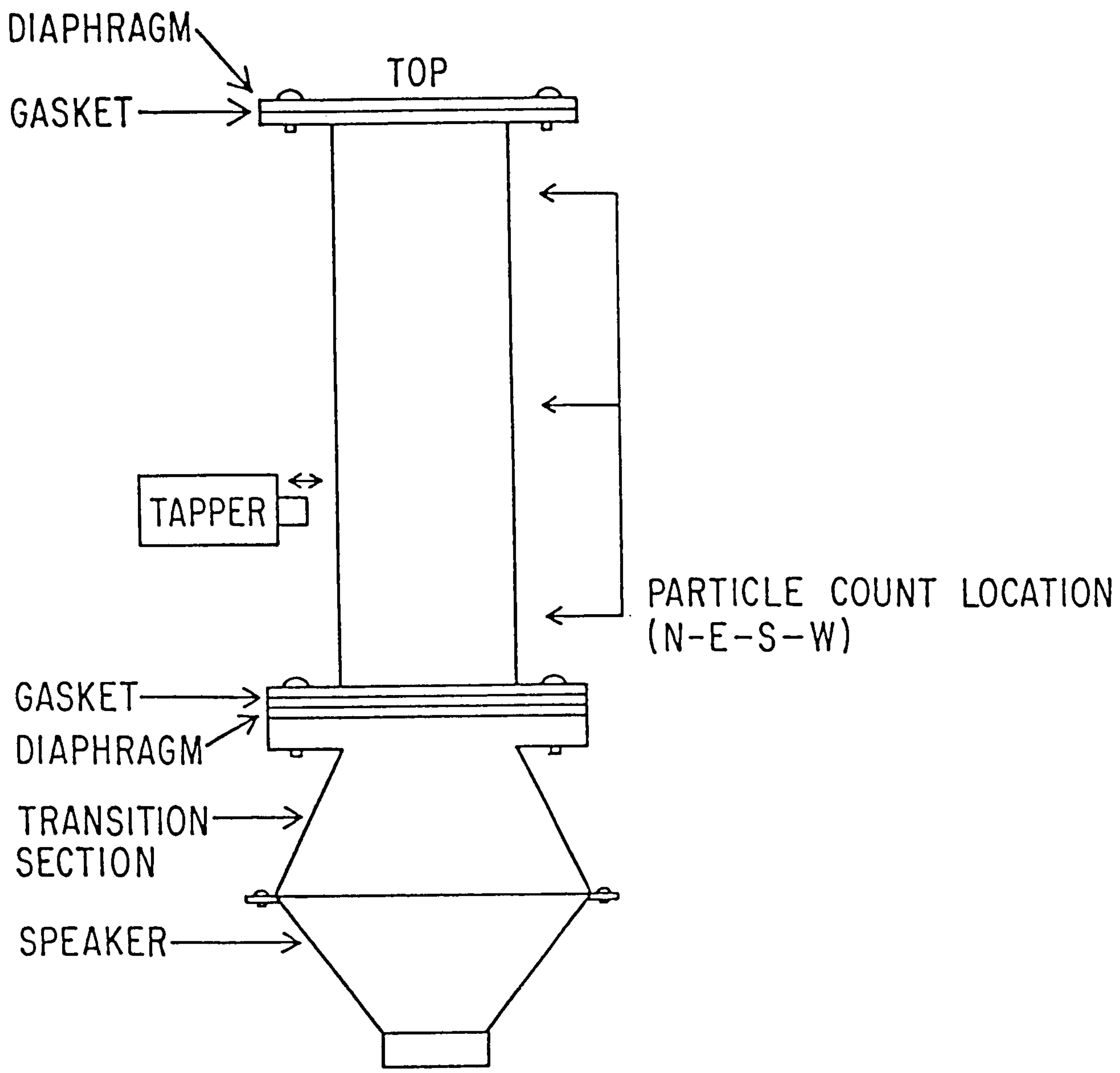


Figure 8: Diagram of Lycopodium Particle Adhesion Test Apparatus.

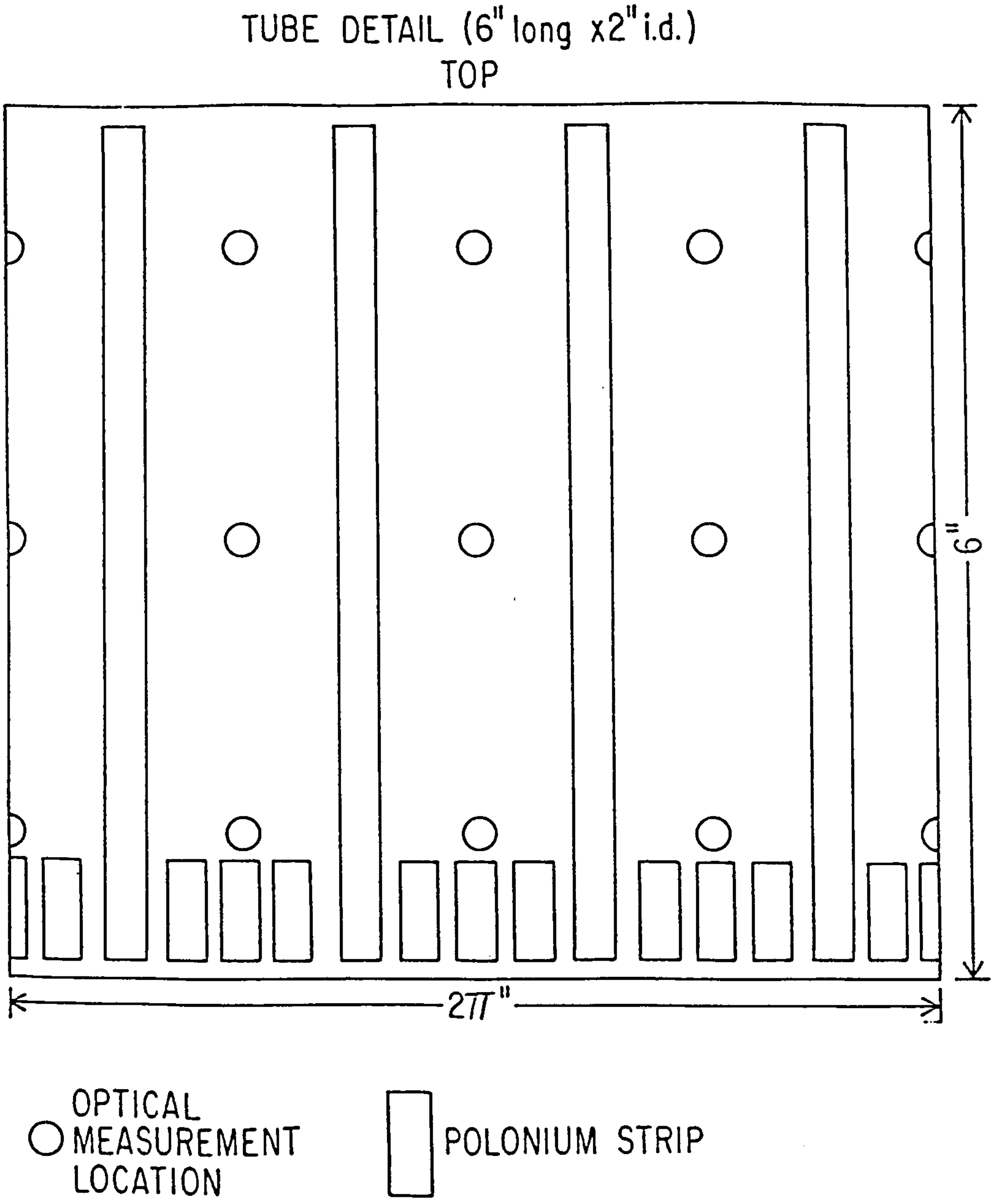
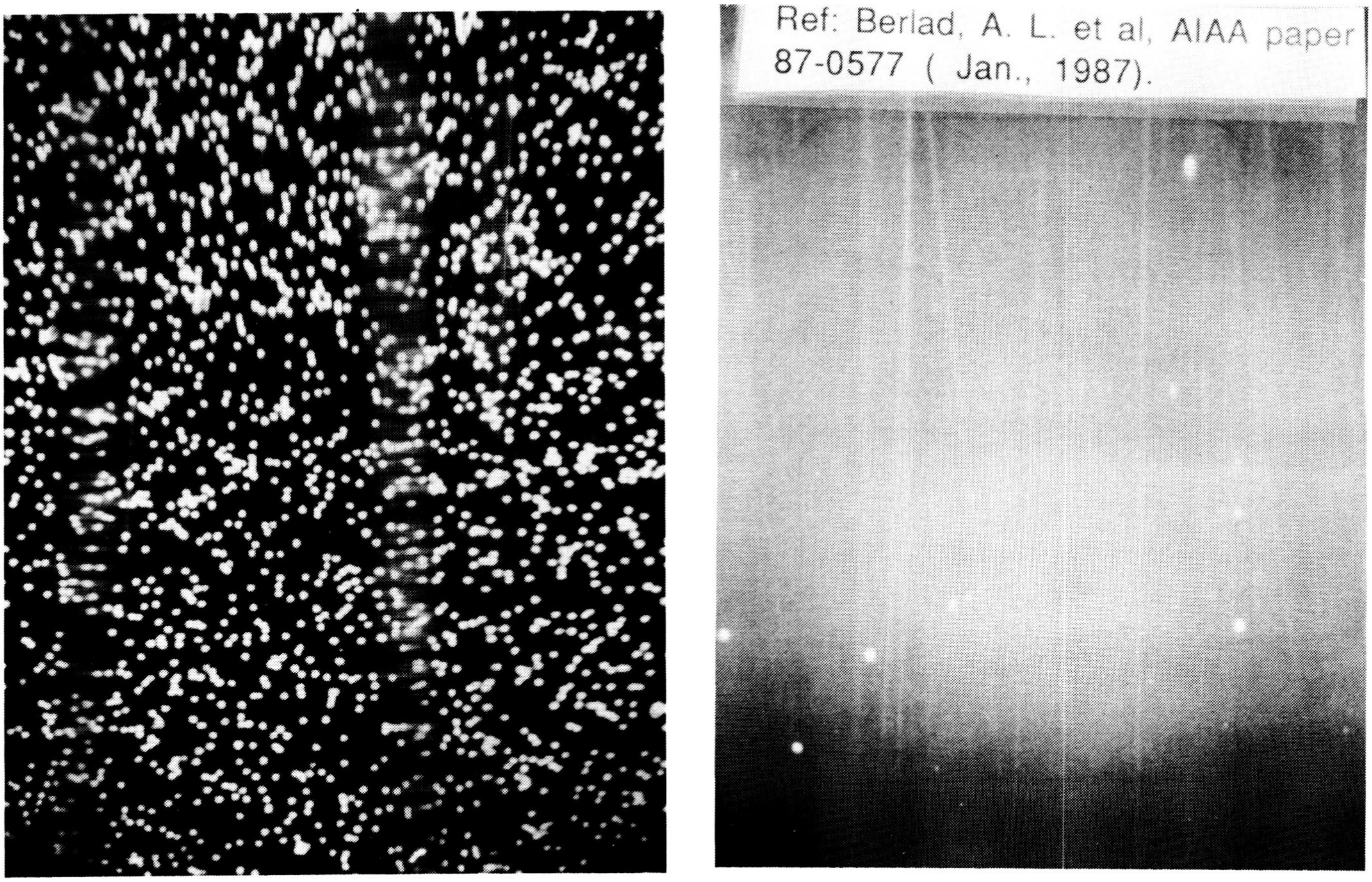


Figure 9: Test Apparatus Tube Detail Showing Wall Placement of Polonium 210 Strip Sources.



Ref: Berlad, A. L. et al, AIAA paper 87-0577 (Jan., 1987).

(a)
Radioactive Sources not in Use

(b)
Polonium-210 Sources in Use

Figure 10: Wall Particle Adhesion for a Gold Coated (ungrounded) Tube.

Mixing: 2.5×10^{-8} Kg Lycopodium at 13 W and 200 Hz for 60 seconds.

Figure 11: Wall Particle Adhesion for a Clear Lexan (ungrounded) Tube.

Mixing: 2.5×10^{-8} Kg Lycopodium at 13 W and 200 Hz for 60 seconds.

conducted without aid of ionizing strip sources. The Figure (10-b) and Figure (11) results derive from experiments with the Polonium-210-containing strips arranged along the inner surface of the test chamber. Further details concering these findings (as well as the dynmamics of particle-particle and particle-wall attachment/detachment processes) are given in reference (22).

It is important to note that the successful mitigation of particle-particle and particle-wall attachment processes is essential to all particle cloud experiments which involve vigorous mixing processes. This includes the body of normal gravity experiments reported previously (e.g., 6, 29,30), as well as our own reduced gravity experiments. It is not evident that previous studies have taken adequate account of mixing-induced agglomerative growth and cloud concentration depletion through surface attachment of particles. Although the use of ionizing sources to inhibit particle-wall attachment is well known, the technique appears not to have been employed previously in particle cloud combustion experiments.

6. LIST OF TABLES

7. LIST OF FIGURES

8. REFERENCES

1. Coward, H. F. and Jones, G. W.: Limits of Flammability of Gases and Vapors. U.S. Bureau of Mines Bulletin 503 (1952).

2. Williams, F. A.: Combustion Theory. 2nd edition. Benjamin Cummings (1985).

3. Berlad, A. L., Huggett, C., Kaufman, F., Markstein, G., Palmer, H. B., and Yang, C. H.: Study of Combustion Experiments In Space. NASA CR-134744 (Nov., 1974).

4. Berlad, A. L.: Combustion of Particle Clouds: in Combustion Experiments in a Zero-Gravity Laboratory, T. H. Cochran (Ed.). Progress in Aeronautics and Astronautics 73, 91 (1981).

5. Hertzberg, M., Conti, R. S., and Cashdollar, K. L.: Spark Ignition Energies for Dust-Air Mixtures: Temperature and Concentration Dependences. Twentieth Symposium (Int'l) on Combustion/The Combustion Institute 1984 (p.1681).

6. Palmer, K. N.: Dust Explosions and Fires. Chapman and Hall, London (1973).

7. Smoot, L. D., Horton, M. D., and Williams, G. A.: Propagation of Laminar Pulverized Coal-Air Flames. Sixteenth Symp. (Int'l) on Combustion, The Combustion Institute, 1976 (p. 375).

8. Horton, M. D., Goodson, F. P., and Smoot, L. D.: Characteristics of Flat, Laminar Coal Dust Flames. Combustion and Flame 28, 187 (1977).

9. Smoot, D. and Horton, M.: Propagation of Laminar Coal-Air Flames. Progress In Energy and Combustion Science 1, 235 (1977).

10. Berlad, A. L. and Joshi, N. D.: Gravitational Effects On The Extinction Conditions for Premixed Flames. Acta Astronautica 12, 539 (1985).

11. Joshi, N. D. and Berlad, A. L.: Gravitational Effects On Stabilized, Premixed, Lycopodium-Air Flames. Comb. Sci. & Tech. 47, 55 (1986).

12. Lovachev, L. A., et. al.: Flammability Limits: An Invited Review. Combustion and Flames 20, 259 (1973).

13. Levy, A.: An Optical Study of Flammability Limits. Proc. Roy. Soc., London A283, 134 (1965).

14. Hamins, A., Heitor, M., and Libby, P.A.: Gravitational Effects On The Structure and Propagation of Premixed Flames. IAF paper 86-279. International Astronautical Congress (1986).

15. Spalding, D. B.: A Theory of Inflammability Limits and Flame Quenching. Proc. Roy. Soc. A240, 83 (1956).

16. Berlad, A. L. and Yang, C. H.: On The Existence of Steady State Flames. Combustion and Flame 3, 447 (1959).

17. Essenhigh, R. H. and Csaba, J.: The Thermal Radiation Theory For Flame Propagation In Coal Dust Clouds. Ninth Symposium (Int'l) on Combustion/Combustion Institute (1963), p. 111.

18. Aly, S. L. and Hermance, C. E.: A Two-Dimensional Theory of Laminar Flame Quenching. Combustion and Flame 40, 173 (1981).

19. Mitani, T.: A Flame Inhibition Theory By Inert Dust and Spray. Combustion and Flame 43, 243 (1981).

20. Joulin, G.: Asymptotic Analysis of Non-Adiabatic Flames. Heat Losses Towards Small Inert Particles. Eighteenth Symposium (Int'l) on Combustion/The Combustion Institute (1981), p. 1395.

21. Kailasnath, K. and Oran, E.: Effects of Curvature and Dilution On Unsteady, Premixed Laminar Flame Propagation. NRL Report #5659 (1985).

22. Berlad, A. L., Joshi, N., Ross, H. and Klimek, R.: Particle Cloud Kinetics In Microgravity. AIAA Paper No. 87-0577 (1987).

23. Gat, N. and Kropp, J. L.: Summary of Activities On The Zero-Gravity Particle Cloud Combustion Experiment. Summary Report on NASA Contract NAS3-23254 (1983).

24. Berlad, A. L., Burns, R. J. and Ross, H. D.: Science Requirements For The Particle Cloud Combustion Experiment (Revision A). NASA document (Jan., 1987).

25. Clavin, P. and Nicoli, C.: Effects of Heat Losses On The Limits of Stability of Premixed Flames Propagating Downwards. Combustion and Flame 60, 1(1985).

26. Oran, E. S., et. al.: A Study of Detonation Structure: The Formation of Unreacted Gas Pockets. Nineteenth Symposium (Int'l) on Combustion/The Combustion Institute (1982), p. 573.

27. Smoot, L. D., Horton, M. D., and Williams, G. A.: Propagation of Laminar Pulverized Coal-Air Flames. Sixteenth Symposium (Int'l) on Combustion (1976), p. 375.

28. Oran, E. S. and Boris, J. P.: Numerical Simulation of Reactive Flows. Monograph, To Be Published (1987).

29. Nagy, John, et. al.: Explosibility of Miscellaneous Dusts. U.S. Bureau of Mines Report on Investigations 7208 (Dec., 1968).

30. Hertzberg, M., Cashdollar, K. L., Zlochower, I., and Ng, D. L.: Inhibition and Extinction of Explosions In Heterogeneous Mixtures. Twentieth Symposium (Int'l) on Combustion/The Combustion Institute, (1984), p. 1691.

31. Berlad, A. L.; On Characterization and Mitigation of Combustion Hazards Involved in the Handling of Particulate Materials. Invited Review. Drying Technology 3, 123 (1985).